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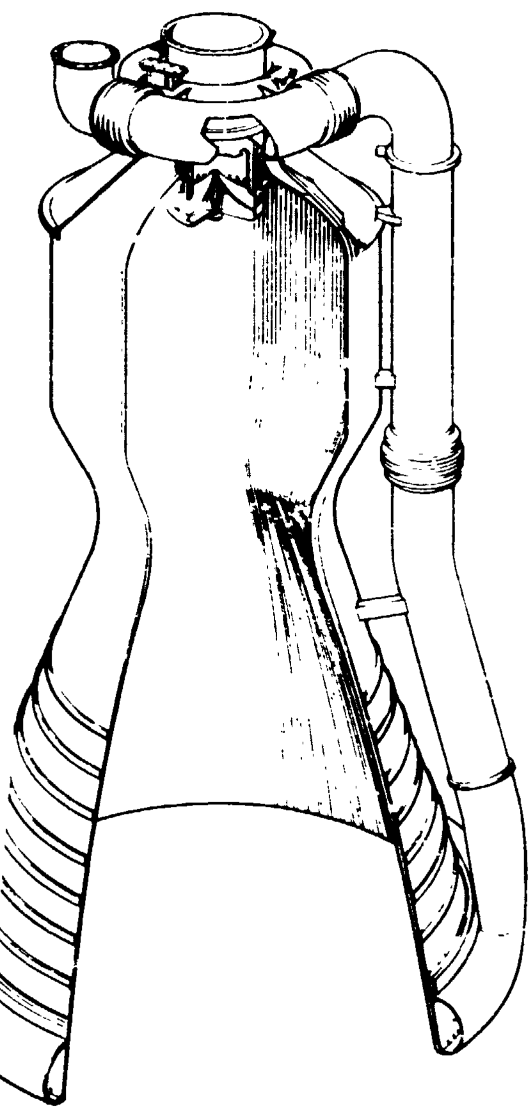

FEASIBILITY STUDY OF A PRESSURE-FED ENGINE FOR A WATER RECOVERABLE SPACE SHUTTLE BOOSTER

VOLUME I
EXECUTIVE SUMMARY

NAS 8-28218

15 MARCH 1972

PREPARED FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

TRW
SYSTEMS GROUP
ONE SPACE PARK • REDONDO BEACH • CALIFORNIA

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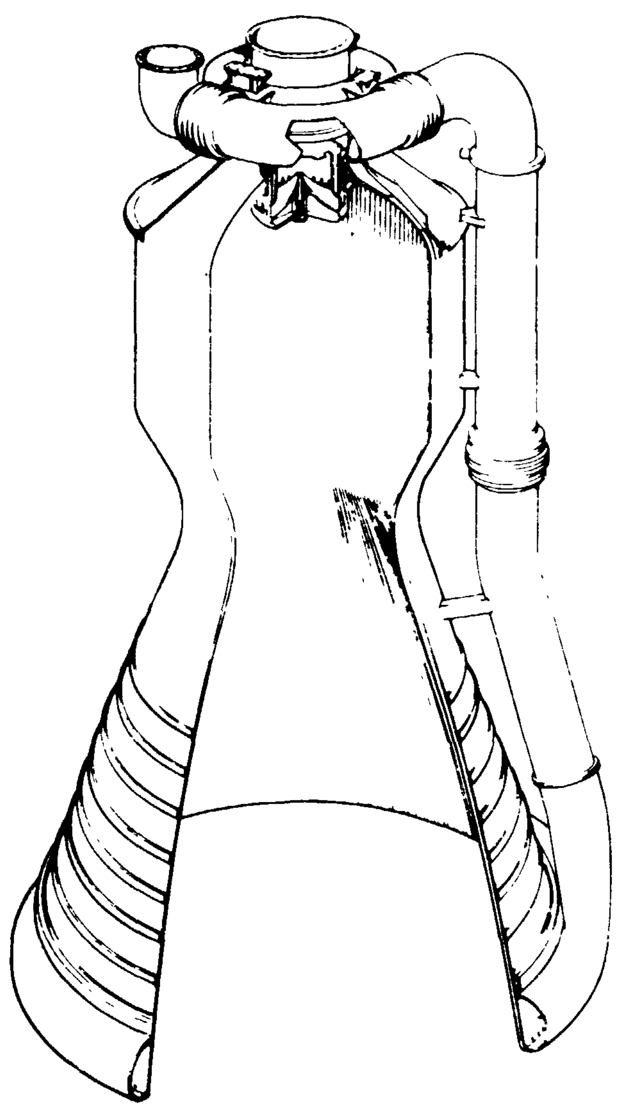

FEASIBILITY STUDY OF A PRESSURE-FED ENGINE FOR A WATER RECOVERABLE SPACE SHUTTLE BOOSTER

VOLUME I
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DRD MA-05

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FOREWORD

This Executive Summary of the Phase B activity on the Feasibility Study of a Pressure Fed Engine for a Water Recoverable Space Shuttle Booster is prepared for the National Aeronautics and Space Administration, Marshall Space Flight Center. The final candidate engine with its alternate variations has been designed and a preliminary design package completed. The enclosed data complete the Executive Volume requirements for MA-05 of Contract NAS 8-28218.

An overall schedule for a PFE program along with program cost is included in the Executive Summary.

CONTENTS

CONTENTS (Continued)

1. INTRODUCTION AND SUMMARY

1.1 GENERAL

The water recoverable reusable pressure-fed engine propulsion stage approach has the potential of offering reliable and economical propulsion in the next decades of space exploration and utilization. The simplicity of the propulsion system, the optimum low pressure operating regime for the engines, the minimum total number of active elements, and the allowable sheer ruggedness of the overall design approach results in a launching stage which virtually guarantees low operational costs. By incorporation of a design philosophy which always drives the design towards minimum total program cost and a requirement that any engineering approach must be accomplished by responsibly generated cost effectiveness results, a derived design approach is taken which provides the end result of minimum cost with high reliability. Because of the strong driving cost payoff functions for such a vehicle, it is necessary that all the required functions of the total vehicle be analyzed in terms of their composite cost effect on the whole program. Unknown areas require that careful risk assessment be made and alternative approaches be evaluated as insurance to meet the overall program requirements and goals.

TRW Systems was awarded contract NAS 8-28218 on 24 November 1971 to perform a 3-month program of engine design and system support to on-going NASA vehicle study contracts and to accomplish Phase A/B preliminary analysis of candidate pressure-fed engines (PFE). The Phase A effort terminated on 19 January 1972 with a documentation of the technically derived design and supporting analysis data and a formal presentation of the results at NASA/MSFC.

1.1.1 Phase A Summary

The Phase A basic program objectives were as follows:

1) Parametric definition of a pressure-fed engine system for thrust levels, propellants, etc.
2) Definition of interface data required by the booster Phase B prime contractor(s) for their particular booster configurations
3) Definition of a preliminary baseline design for the pressure-fed engine system approved by NASA

4) Determination of required engine operational characteristics
5) Determination of research, design, test and evaluation, production and operational costs for the selected systems
6) Identification of cost/performance/mission effectiveness
7) Recommendations.

For the Phase A/B type of design studies in this program two propellant combinations were considered: LO_2/RP-1 and LO_2/C_3H_8. The Phase B effort was directed to consideration of the LO_2/RP-1 combination. As a Phase A/B study to determine the feasibility of the PFE for the Space Shuttle booster the design studies were necessarily limited to key efforts which had major impacts on the technological feasibility assessment of the concept. As a result, the stress, thermal, and dynamic studies were by no means complete for final design purposes. They were sufficiently completed to provide engineering evaluation of the overall concept.

This Executive Volume presents an overview of the results of the analyses conducted in support of the selected engine system for the pressure-fed booster stage. The costing analysis of the TRW Systems pressure-fed engine program requirements are presented under separate cover in SE-019-008-2H-C (Part II), Cost Estimating Data. The development plan for the pressure-fed engine (PFE) is also presented under separate cover in SE-019-008-2H-B (Part I). The PFE design summary is presented in the Design Data Book, SE-019-011-2H. The report Preliminary Design Package, SE-019-013-2H presents the preliminary design package. A detailed mass properties summary is presented in the Mass Properties Report, SE-019-015-2H.

1.2 RECOMMENDED CONFIGURATION CHARACTERISTICS

The design approach (Figure 1.2-1) to the TRW PFE was one of simplifying the engine to its most rudimentary functions. The engine features a 24" diameter centrally located injector with LO_2 entering the engine axially as shown. The diameter of the LO_2 feeder is set identical to the main vehicle feed ducting with feed velocities on the order of 20 fps. The LO_2 enters the chamber radially through 36 primary and 36 secondary slots. These slots are on the order of 3: x 0.7" and as such do not possess any critical tolerance dimensions. The fuel flows through $\sim$ 0.7" annulus in

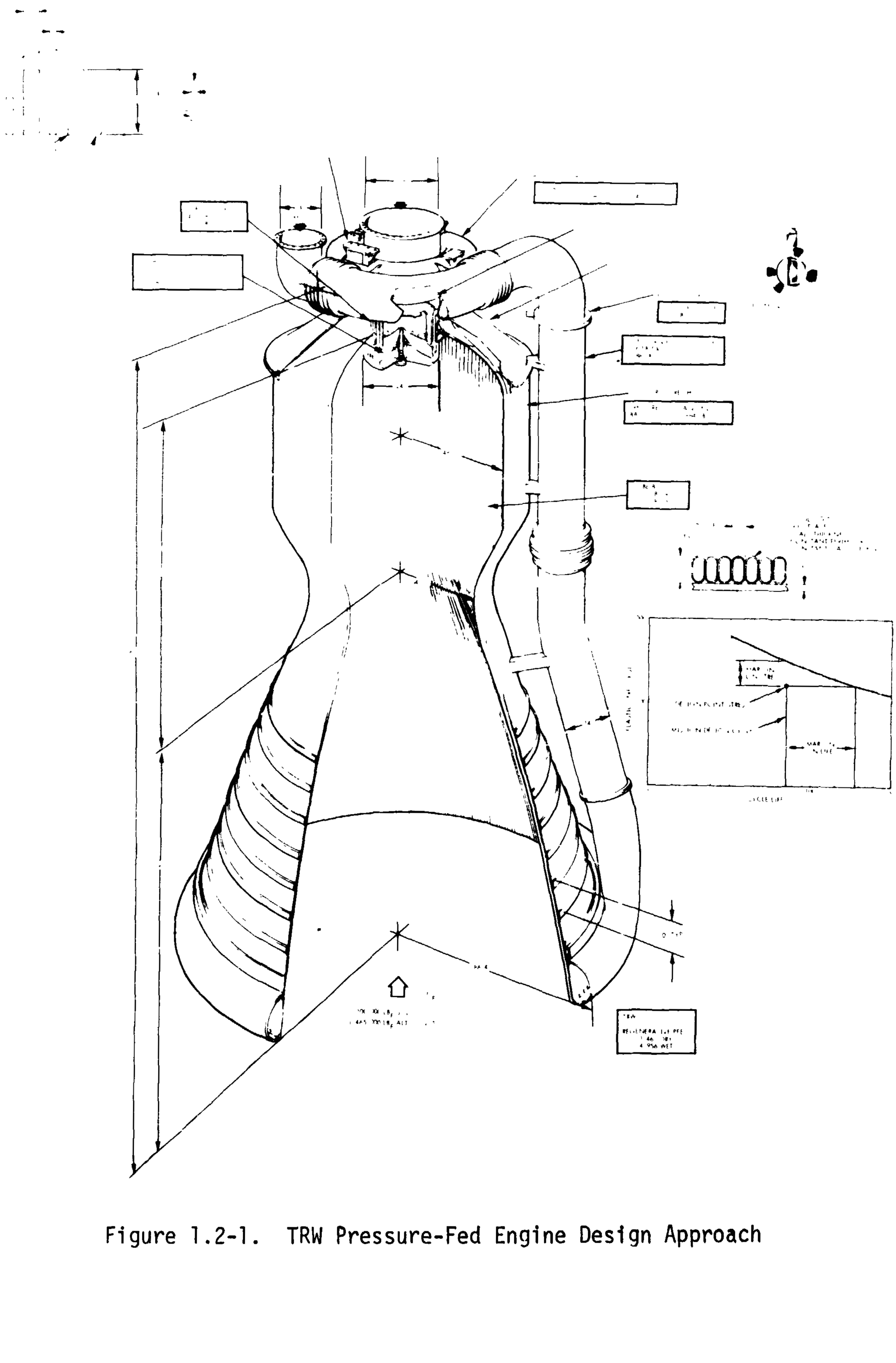

Figure 1.2-1. TRW Pressure-Fed Engine Design Approach

an axial direction where it intercepts the radially flowing LO_2. The effective metering orifices then are not critical tolerance elements and are easily inspected. The cryogenic LO_2 temperatures are separated from the ambient temperature fuel by a void to present undesireable temperature interactions. Ignition is achieved with standard TEA/TEB, similar to the F-1 system.

The fuel enters the engine through an external feeder duct of nominal 14" diameter. A single up pass cooling circuit is utilized. The fuel enters the injector at an estimated 20 °F temperature higher than the supply temperature.

The propellant shut off valves are of the wafer type and serve only as on-off valves. The actuators can be driven by: (1) APU hydraulic power, or (2) the pressurized RP-1, or (3) the pressurization system gases. These valves are $\sim$ 14" for the fuel and $\sim$ 18" for the LO_2.

The tube bundle consists of 940 tubes. The approach taken is to select a tubing sizing which is of standard mill run. The tubes are then shaped only with respect to width in the chamber with no tube wall drawing required. This means a constant wall thickness, constant perimeter tube is possible, resulting in minimum tube costs. There are no critical dimensions for the tube bundle for the low heat flux PFE.

The chamber pressure shell extends to an area ratio of $\sim$ 1.4:1. The remainder of the nozzle is banded. The entire shell, tube, and banding is integrally brazed as a unit.

The gimbal mount is a 4 bearing mount, placed around the oxidizer inlet in a symmetrical gimbal ring.

The life of the engine is predicted to easily meet a mission requirement of 50 missions from a pressure and thermal fatigue standpoint. This life is particularly enhanced by using all the fuel for cooling to minimize the tube wall temperatures.

The engine is fabricated from INCO 718 for high corrosion resistance. Ni 200 tubing would increase the life to greater than 100. The weight of the engine is 11,467 lbs dry and 14.956 wet; these weights result in higher thrust/weight ratios than conventional engines can give, primarily because of the 660 lb central injector element.

The overall envelope of the engine is $\sim$ 172.8" O.D. by 261.5" to the plane of the gimbal ring.

1.3 INJECTION SELECTION

TRW Systems has taken the approach that the injector selection is the major factor in the PFE concept. The single most important driver in any PFE development program, based upon past large engine development, can be the occurrence of stability problems. The TRW coaxial printle injector is the <u>only</u> concept used in a major NASA development (LMDE) which experienced <u>no</u> combustion stability problems. In research programs it has been scaled to 250,000 lbf at 300 psia and found to be dynamically stable. In addition, independent study by Dynamic Sciences, in support to this contract, has indicated that the approach should be dynamically stable to high frequency instability modes even at the largest size PFE to be considered for any NASA booster configuration.

In addition to predicted stability insensitivity, the element possesses the ability to incorporate throttling and/or face shutoff into the engine with minimum impact upon the overall engine design. Some thrust modulation is required on booster vehicles to meet vehicle acceleration and dynamic head limitations. To meet g-limitations, selected engine cutoff shcemes have been proposed; however, the cutoff engine cannot be adequately protected without some active cooling. Further, pressure modulation of thrust is sluggish and at the end of the maximum q-limit period, maximum thrust i. again required. As a consequence the throttling would be most effect' ly accomplished by mechanical throttling at the early flight q-control p ds and by pressure throttling at the end of the flight to minimize overa pressurization system weight in a PFB. It is the absolute minimum weight injector design because it utilizes only one pressure dome in the engine. A key factor is that it is fabricated from one single material; as a result there is no need for any h h conductivity, dissimilar metals which can be a cause of internal corrosion.

The basic injector concept is illustrated in Figure 1.3-1 and 1.3-2. In Figure 1.3-1 a fixed thrust version is shown. The O_2 enters the injecto axially from the main feed du t and flows radially outward through 36 primary

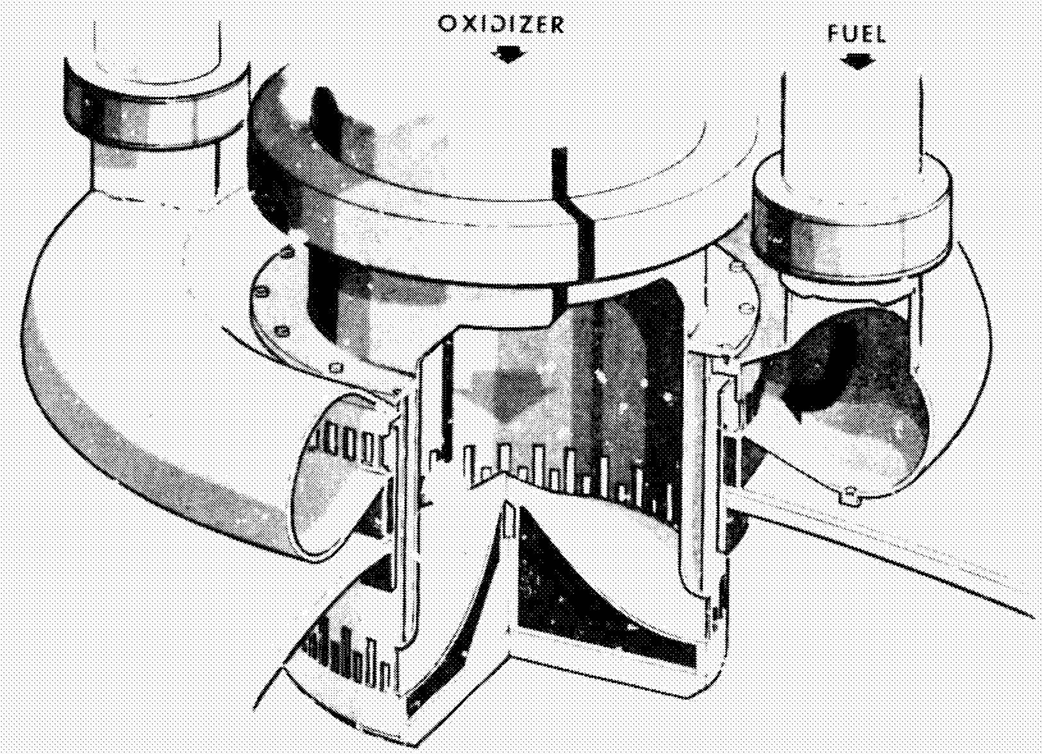

Figure 1.3-1. Fixed Coaxial Injector Concept, Pressure-Fed Engine

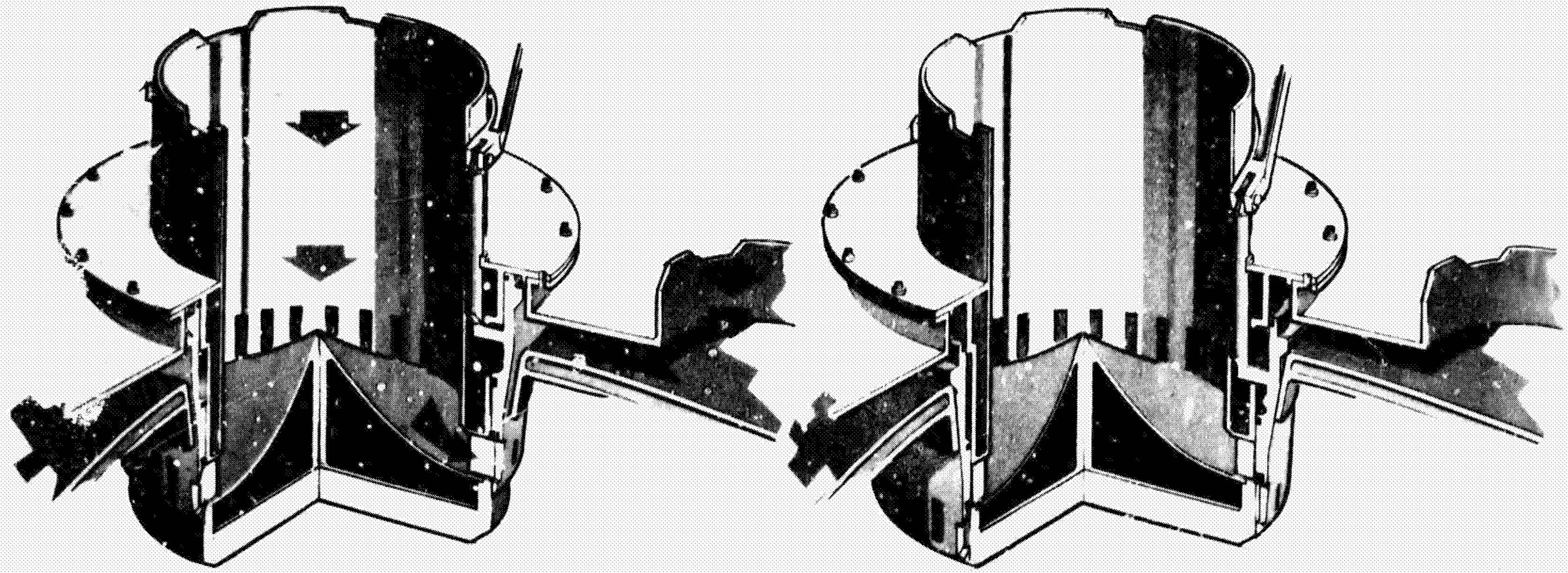

Figure 1.3-2. Throttleable Coaxial Injector Concept for the Pressure-Fed Engine

and 36 secondary rectangular orifices. These orifices are approximately 3.00 x 0.75 inches for the primary slots. The fuel enters through a distributing manifold and flows directly axially as a thin $\sim$ 0.7 inch continuous annulus. The fuel sheet is intercepted by the oxygen jets and integral mixing and atomization preparation for efficient, controlled combustion is accomplished. The unit is located directly in the center of the combustion chamber pressure dome which is approximately a $\sim$ 2:1 elliptical head. The approximate injection diameter is $\sim$ 24 inches for a 1,200K engine.

As can be readily appreciated there are <u>no</u> key critical injector dimensions requiring tight tolerance control. The orifice areas are large enough to pass minor debris and are readily inspectable. Because of demonstrated cold head end temperature zones, it is not necessary to use special high conductivity materials for the injector (such as copper which may introduce an electromechanical attack problem). The minimum number of parts and single material part with large orifices results in an extremely rugged part, virtually guaranteed to possess extensive reuse life capability.

The coaxial injector approach allows the incorporation of mechanical throttling (Figure 1.3-2) into the design with a minimum of difficulty. This is accomplished by the addition of the sleeve as shown. This sleeve is externally actuated by hydraulic or electromechanical means. It can be continuously throttled or step throttled. As illustrated it is a direct application of the LMDE technology base.

As the PFE is further analyzed it may be found that it is highly desireable to add the feature of face shut-off to the PFE. This would be done to prevent any sea water entry into the engine. It is accomplished by simply closing the throttling sleeve. In application, after boost termination, the residual propellants vaporize off, and the sleeve is closed, with perhaps, 50 psia of pressurant gas locked up behind the face. This can be demonstrated in repeated tests in previous TRW programs.

2. DESIGN CONFIGURATION

2.1 CANDIDATE CONFIGURATION

The design approach to the TRW PFE has been one of simplifying the engine to its most rudimentary functions. The engine features a 24" diameter centrally located injector with oxidizer entering the chamber axially as shown in Figure 2.1-1. The diameter of the oxidizer feeder is set identical to the vehicle feed ducting and flow velocities are on the order of 20 fps. The oxidizer is turned at the injector tip and enters the chamber radially through 36 primary and 36 secondary slots. These slots are on the order of 3" x 0.7" and as such do not possess any critical tolerance dimensions. The fuel flows through ∿ 0.7" annulus in an axial direction where it intercepts the radially flowing oxidizer. The effect of dimensional differences on these metering orifices is not critical. They are easily cut by standard manufacturing practices and readily inspected. The cyrogenic oxidizer temperatures are separated from the ambient temperature fuel by a void to prevent undesireable temperature interactions. Ignition is achieved with standard TEA/TEB, similar to the F-1 system.

The fuel enters the engine through an external feeder duct of nominal 14" diameter. A single counter pass regenerative cooling circuit is utilized. The fuel enters the injector at an estimated 200°F temperature higher than the supply temperature.

The propellant shutoff valves are of the wafer type and serve only as on-off valves. The actuators would be driven by: (1) APU hydraulic power, or (2) the pressurized RP-1 or (3) the pressurization system gases. These valves are ∿ 14" for the fuel and ∿ 16" for the oxidizer.

The design chamber tube bundle consists of 940 tubes. The approach taken is to select a tubing sizing which is of standard mill run. The tubes are then shaped only with respect to width in the chamber with no tube wall drawing required. This means a constant wall thickness, constant perimeter tube is possible, resulting in a minimum tube cost. There are no critical dimensions for the tube bundle for the low heat flux PFE.

The chamber shell extends to an area ratio of ∿ 1.4:1. The remainder

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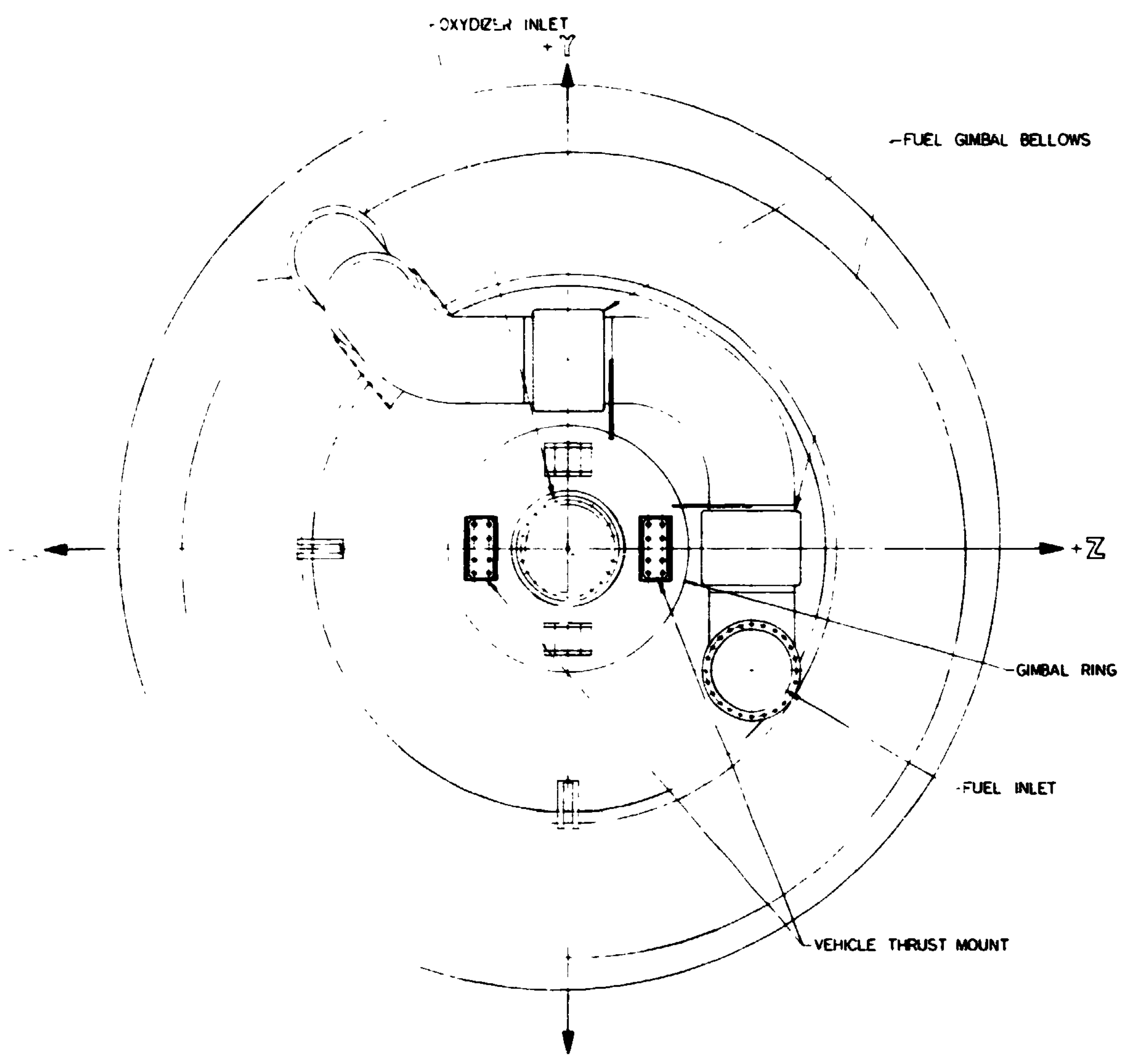

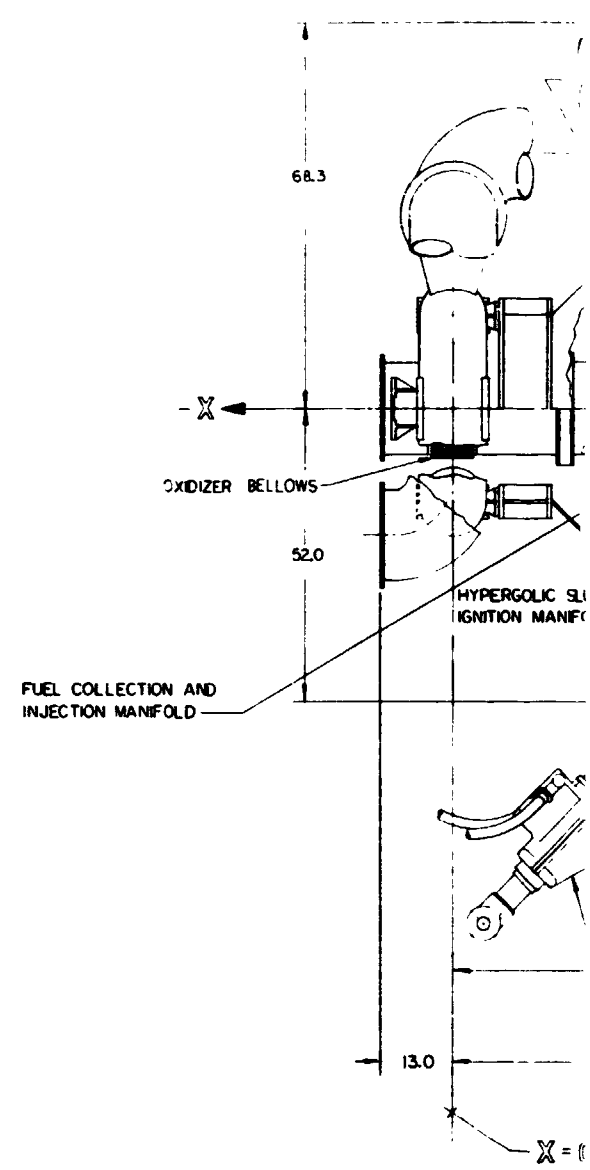

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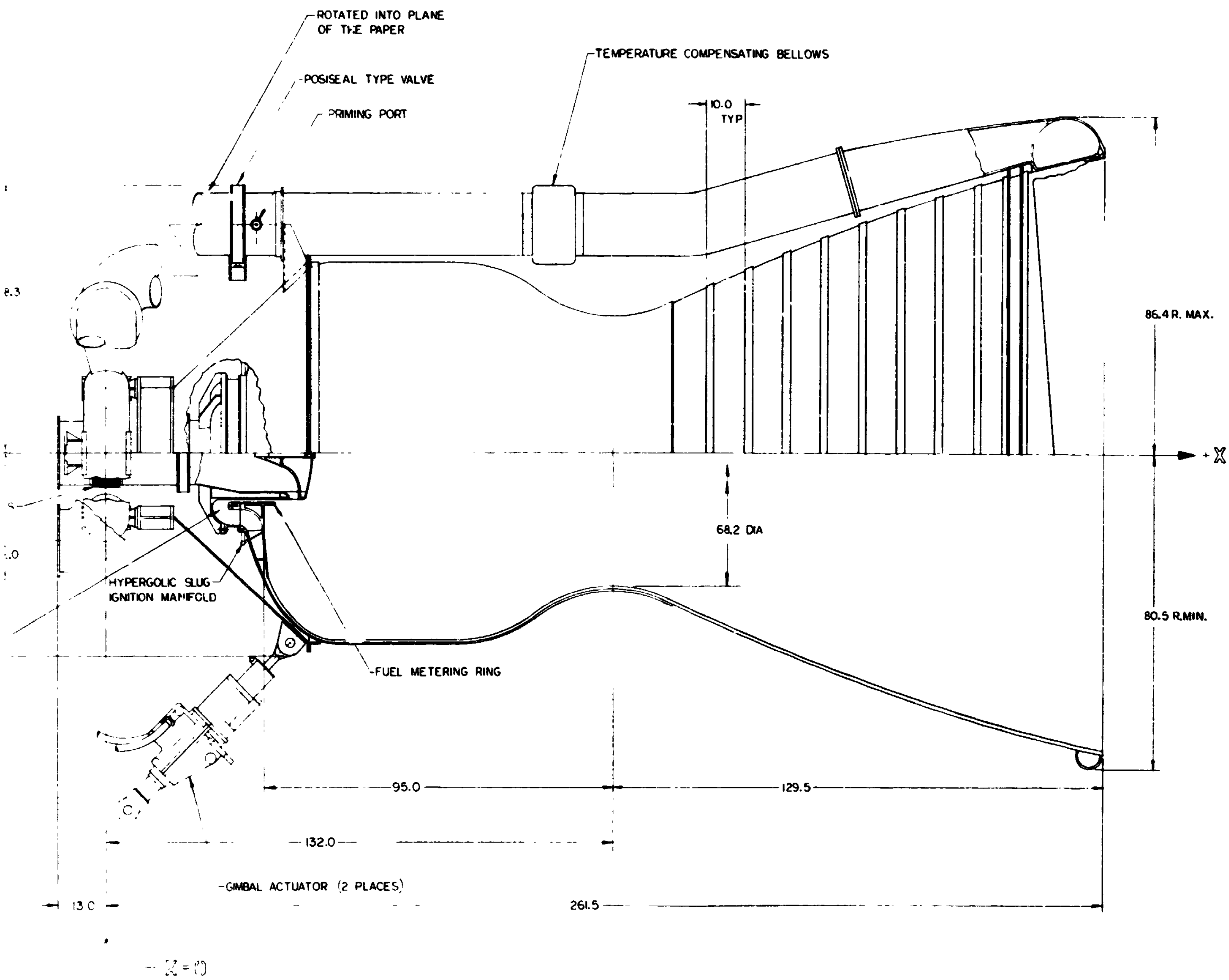

Figure 2.1-1. TRW Pressure-Fed Engine Candidate for Space Shuttle

of the nozzle is banded. The entire shell, tube, and banding is integrally brazed as a unit.

The gimbal mount is a 4 bearing mount, placed around the ozidizer inlet in a symmetrical gimbal ring.

The life of the engine is predicted to easily meet a mission requirement of 50 missions from a pressure and thermal fatigue standpoint. This life is particularly enhanced by using all the fuel for cooling to minimize the tube wall temperatures.

2.1.1 Weight and Envelope Summary

The engine is fabricated from INCO 718 for high corrosion resistence. The weight of the engine is 11,467 lbs dry and 14.956 lbs wet; these weights result in a higher thrust/weight ratios than conventional engines can give, primarily because of the 660 lb injector element.

The overall envelope of the engine is ∿ 172.8" O.D. by 261.5" to the plane of the gimbal ring.

The static and dynamic envelopes for the TRW PFE are shown in Figure 2.1-2 and 2.1-3 for a 6° gimble angle.

The engine approach results in a relatively simple engine approach. A blow-apart of the engine is shown in Figure 2.1-4 with every major part indicated. As contrasted to a high pressure, pump fed engine the minimized major part summary is obvious.

2.1.2 Preliminary Specification for TRW Pressure-Fed Engine

The preliminary specifications for the TRW candidate PFE are tabulated in Table 2.1.2-1.

2.1.3 Hydraulic Requirements and Optimization

The engine component configurations were optimized by selecting those configurations which minimized total vehicle weight by comparing the effect of changes in component pressure drop and component weight on vehicle weight. Representative exchange factors for the PFB are as follows:

$$\left.\begin{array}{l} \dfrac{\Delta W_{VEHICLE}}{\Delta W_{ENGINES}} = 5 \text{ lb/lb} \\[2ex] \dfrac{\Delta W_{VEHICLE}}{\Delta P_F} = 1715 \text{ lb/psi} \end{array}\right\} \lambda \simeq 0.85 \text{ for this vehicle}$$

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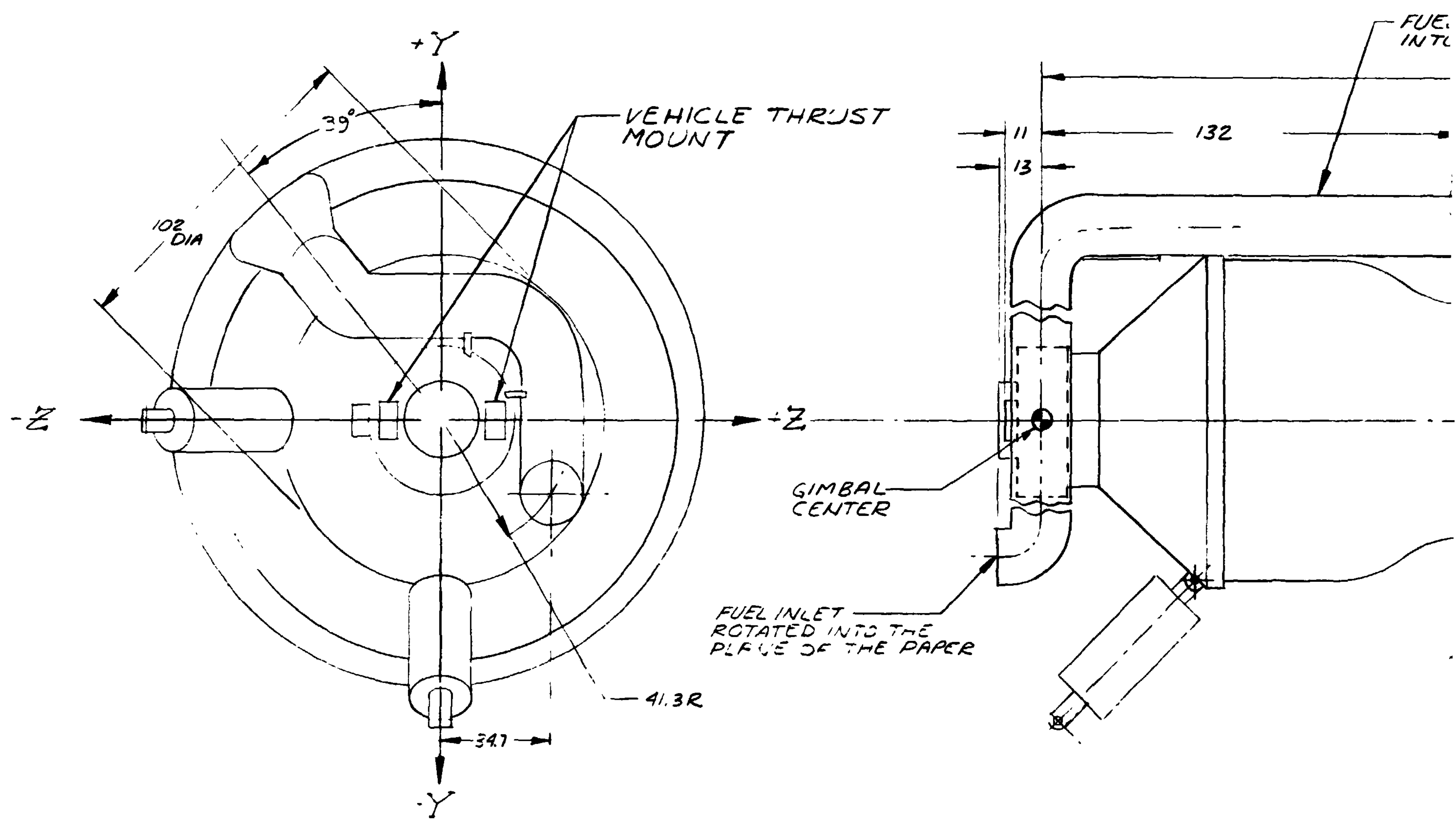

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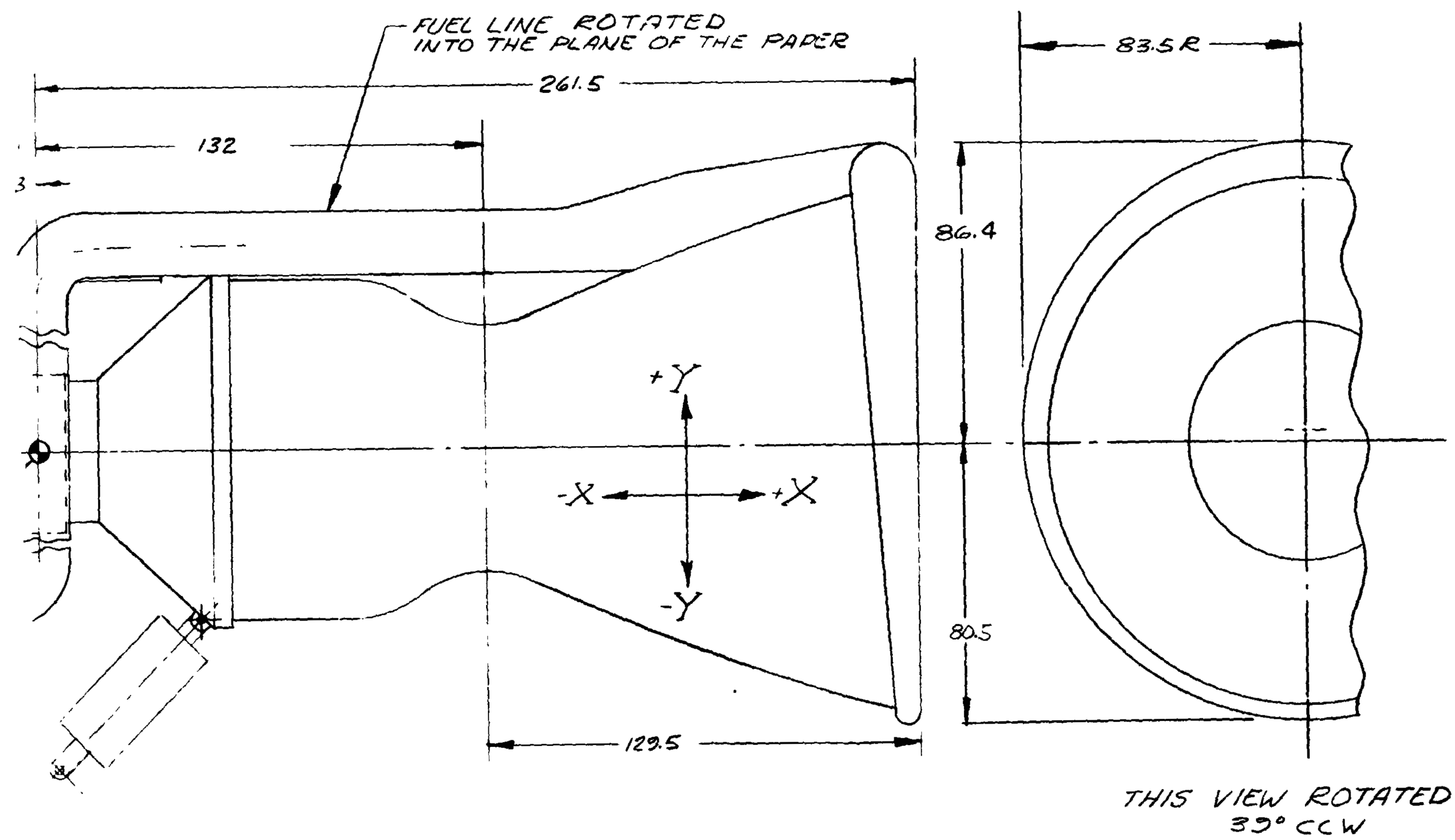

Figure 2.1-2. Static Envelope — Candidate PFE

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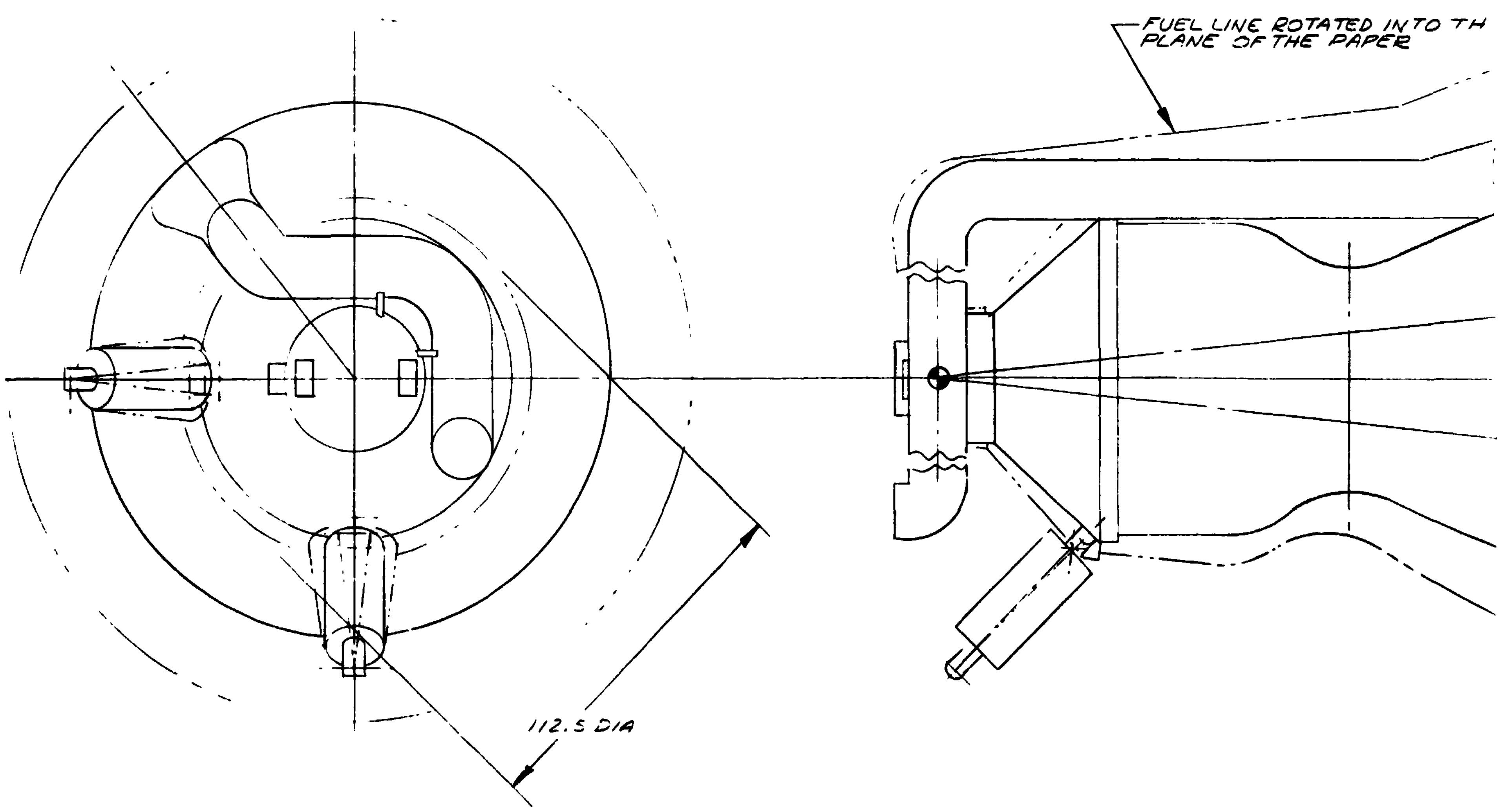

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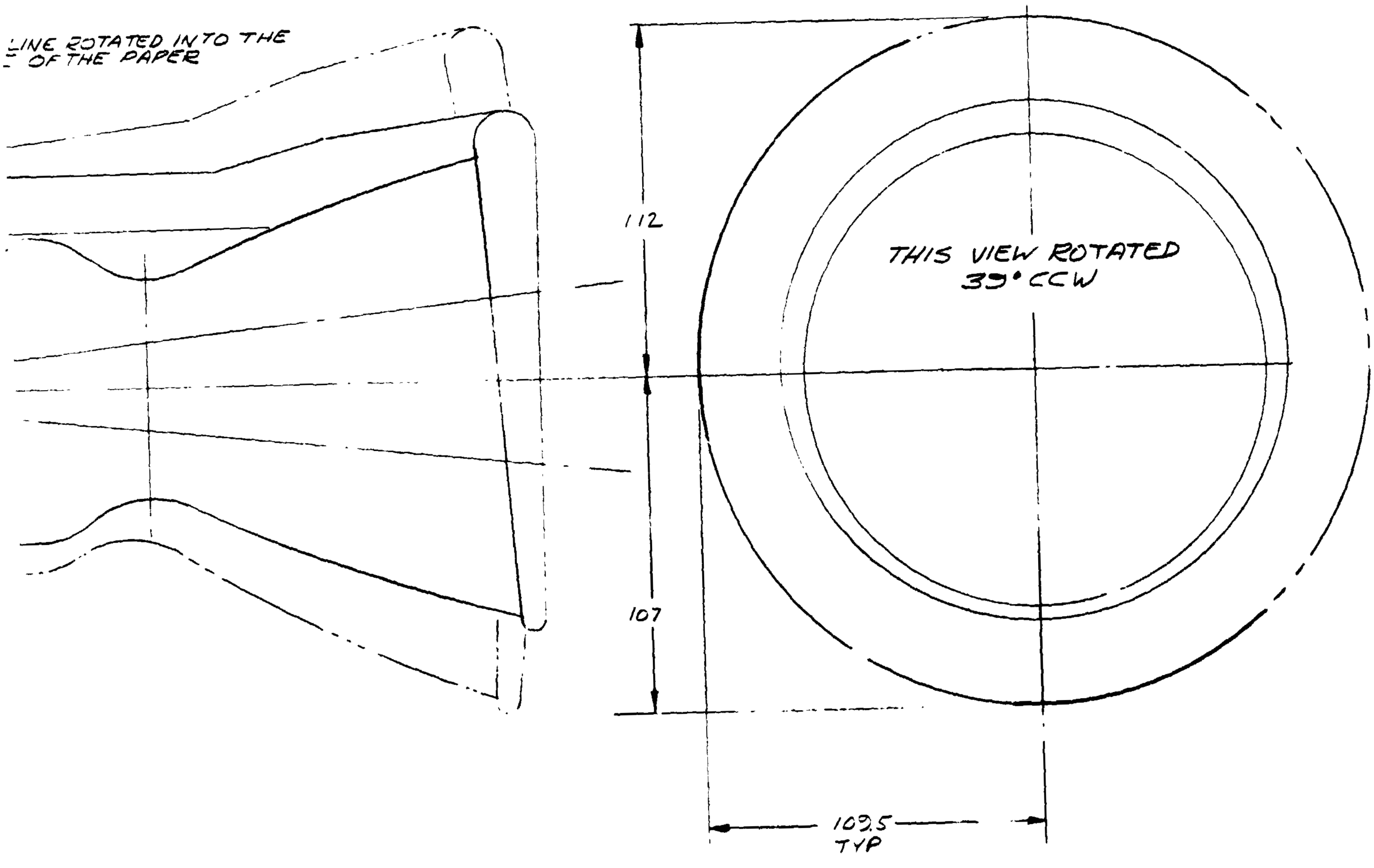

Figure 2.1-3. Dynamic Envelope — Candidate PFE

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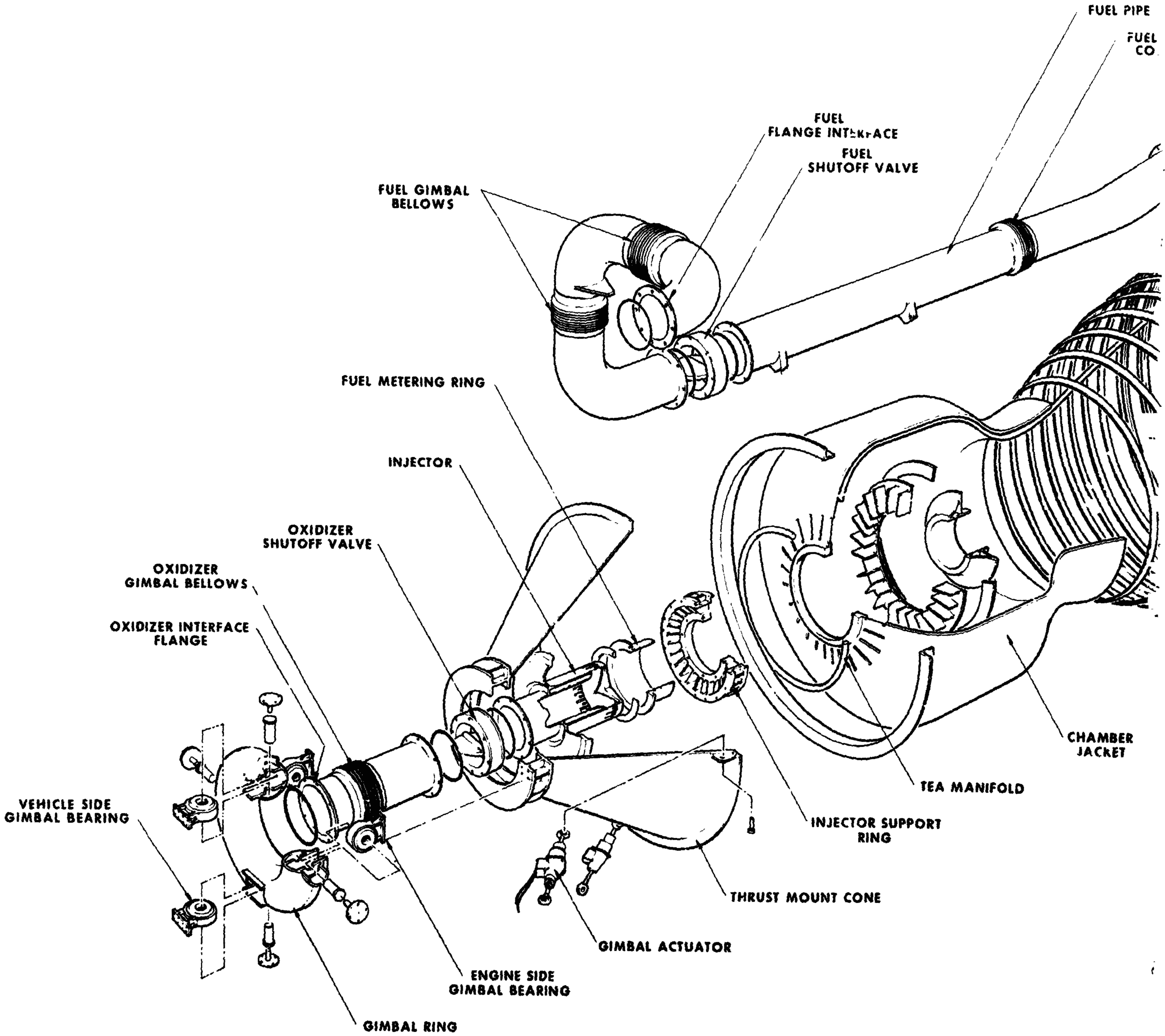

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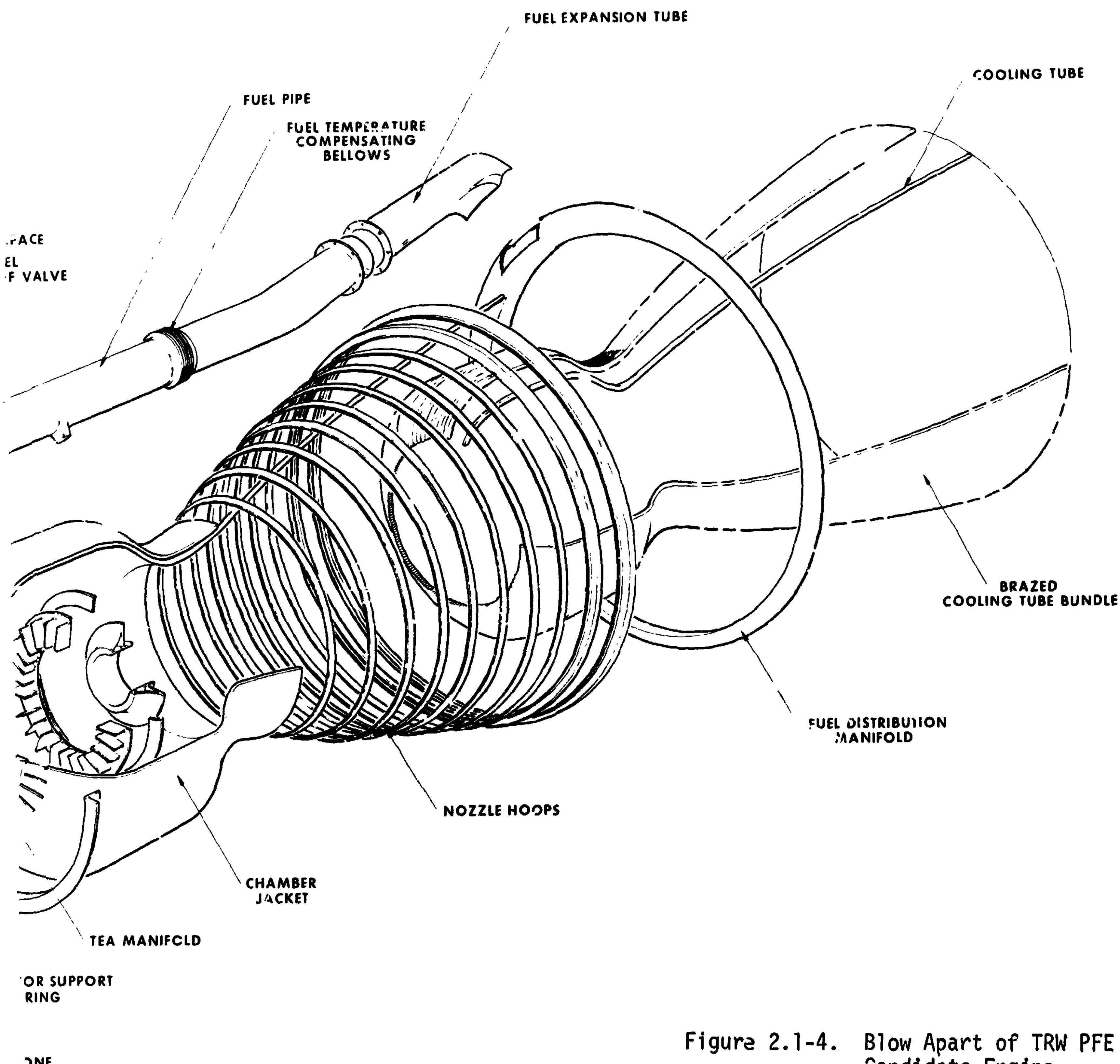


Figure 2.1-4. Blow Apart of TRW PFE Candidate Engine

Table 2.1.2-1. Preliminary Specification – Space Shuttle Booster Pressure Fed Engine

PARAMETER	REQUIREMENT
Sea Level Thrust *	1.2×10^6 lbf
Sea Level Steady State Thrust Repeatability *	+ 36,000 lbf - 36,000 lbf
Vacuum Thrust Level *	1.47×10^6 lbf
Vacuum Thrust Level Repeatability *	+ 45,000 lbf - 45,000 lbf
Propellants	
. Oxidizer	LOX
. Fuel	RP-1
Mixture Ratio	2.4
Mixture Ratio Tolerance *	± 0.048
Propellant Utilization Mixture Ratio Variation (Allowable Maximum)	± 0.24
Chamber Pressure (Nominal)	250 psia
Nozzle Expansion Ratio	5:1
Interface Pressures (Minimum Required)	
. Oxidizer	360 psia
. Fuel	380 psia
Propellant Supply Temperatures	
. Oxidizer	-280°F
. Fuel	+65°F
Sea Level Specific Impulse (Nominal)	227.3 lbf sec/lbm
Sea Level Specific Impulse (3σ minimum)	225.0 lbf sec/lbm
Vacuum Specific Impulse (Nominal)	276.0 lbf - lbf sec/lbm
Vacuum Specific Impulse (3σ minimum)	273.3 lbf - lbf sec/lbm
Throttle Range	
. Pressure	To 70% of Engine Thrust
. Engine	< 60 % of Engine Thrust
Throttle Response	1 second (90% of Commanded Change)

* Defined at nominal conditions

Table 2.1.2-1. Preliminary Specification — Space Shuttle Booster Pressure Fed Engine (Continued)

PARAMETER	REQUIREMENT
Static Envelope	
. Length (overall)	275 inches
. Length (from Gimbal center line)	262 inches
. Exit Diameter	173 inches
. Head End Radius	69 inches
Thrust Vector Control (TVC) System	Gimbal (baseline)
TVC Angle	± 6°
TVC Slewrate	10 deg/sec
TVC Acceleration	3 rad/sec^2
TVC Bandwidth	8 CPS
Mission Burn Time	150 seconds
Life (MBO)	50
Startup Time (to 90% Pc)	3 ± 0.050 seconds
Startup Overshoot (Pc)	25 psi
Startup Overshoot (Pc settling time)	200 ms
Startup Rate (maximum)	700,000 lbs/sec maximum
Shutdown Rate	TBD
Minimum Shutdown Time (to 10% Pc) (Engine Capability)	1.0 seconds
Shutdown Impulse Repeatability (Engine Capability)	± 40,000 lbf/seconds
Side Load Moment	Equivalent 20g Lateral Acceleration
Slap Down Loads	20g, TBD Impact Velocity
Thrust Vector Alignment	± .25°
Maximum Outside Surface Temperature	300°F
Electrical Power	300 Watts maximum
. Startup	200 Watts maximum
. Steady State	200 Watts maximum
. Shutdown	200 Watts maximum
Number of Starts (MBO)	100
Propellant Filtration	2500μ
Shutdown Mode	Injector Face Shutoff
Command Voltage Range (Inclusive all operations)	0-10 V

Table 2.1.2-1. Preliminary Specification — Space Shuttle Booster Pressure Fed Engine (Continued)

PARAMETER	REQUIREMENT
Comoustion Stability (100% Overpressure Bomb Recovery - measured to ± 10% nominal Pc)	50 M.S.
Weight	
. Dry	12,000 lbs
. Wet	15,500 lbs
Moment of Inertia (Wet) (Measured about engine gimbal)	
. Ixx	5056 SL FT^2
. Iyy	28895 SL FT^2
Actuation Mechanisms	
. SOV	Pneumatic - 380 psia
. Throttle Actuator	Hydraulic (Fuel) - 380 psia
. Gimbal Actuator	Hydraulic (Fuel) - 3000 psia
SOV Leakage	10 SCIM GN_2 @ 380 psia
Structural Criteria	MSFC Handbook - 505
. Min. Yield F.S.	
. Min. Ult. F.S.	
. Proof Pressure Factor	
. Burst Pressure	
Material Prop. & Design Allow.	MIL-HDBK-5
Fracture Mechanics Criteria	Yes
Dynamic Stability Requirement	Yes
Failure Criteria	
. Electrical	FO/FS
. Mechanical	F/S

$$\frac{\Delta W_{VEHICLE}}{\Delta P_o} = 2825 \text{ lb/psi}$$

$$\frac{\Delta W_{VEHICLE}}{\Delta P_c} = 4540 \text{ lb/psi}$$

$\lambda \simeq 0.85$ for this vehicle

The hydraulics optimization was carried out for the following:

- Chamber contraction ratio
- Fuel and ozidizer valve diameter
- Regen fuel supply duct diameter
- Regen tubing

The results are presented in Figures 2.1.3-1 to -5. The optimum chamber contraction ratio is approximately 2.2. The optimum fuel and oxidizer valve diameters are 14 and 16 inches, respectively. The optimum regen fuel duct diameter is also approximately 14 inches. The effect on diameter

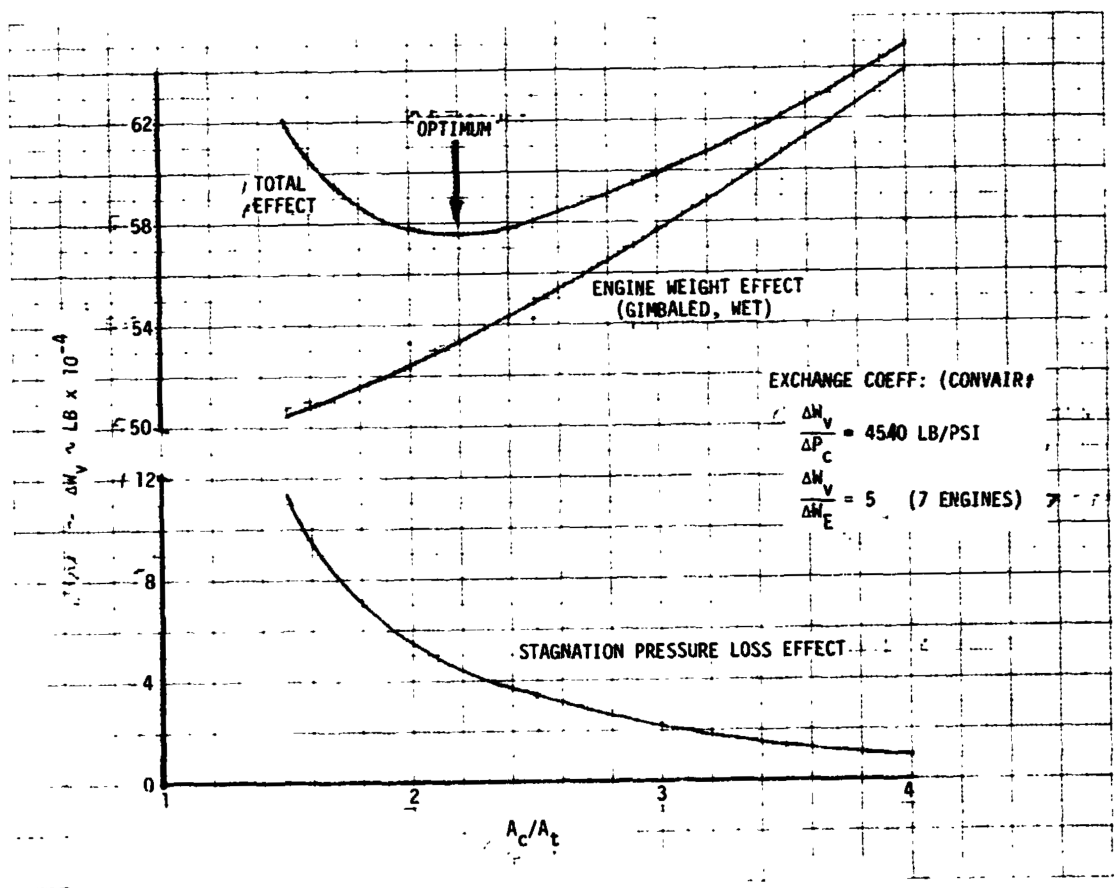


Figure 2.1.3-1. Chamber Contraction Ratio Optimization for TRW PFE

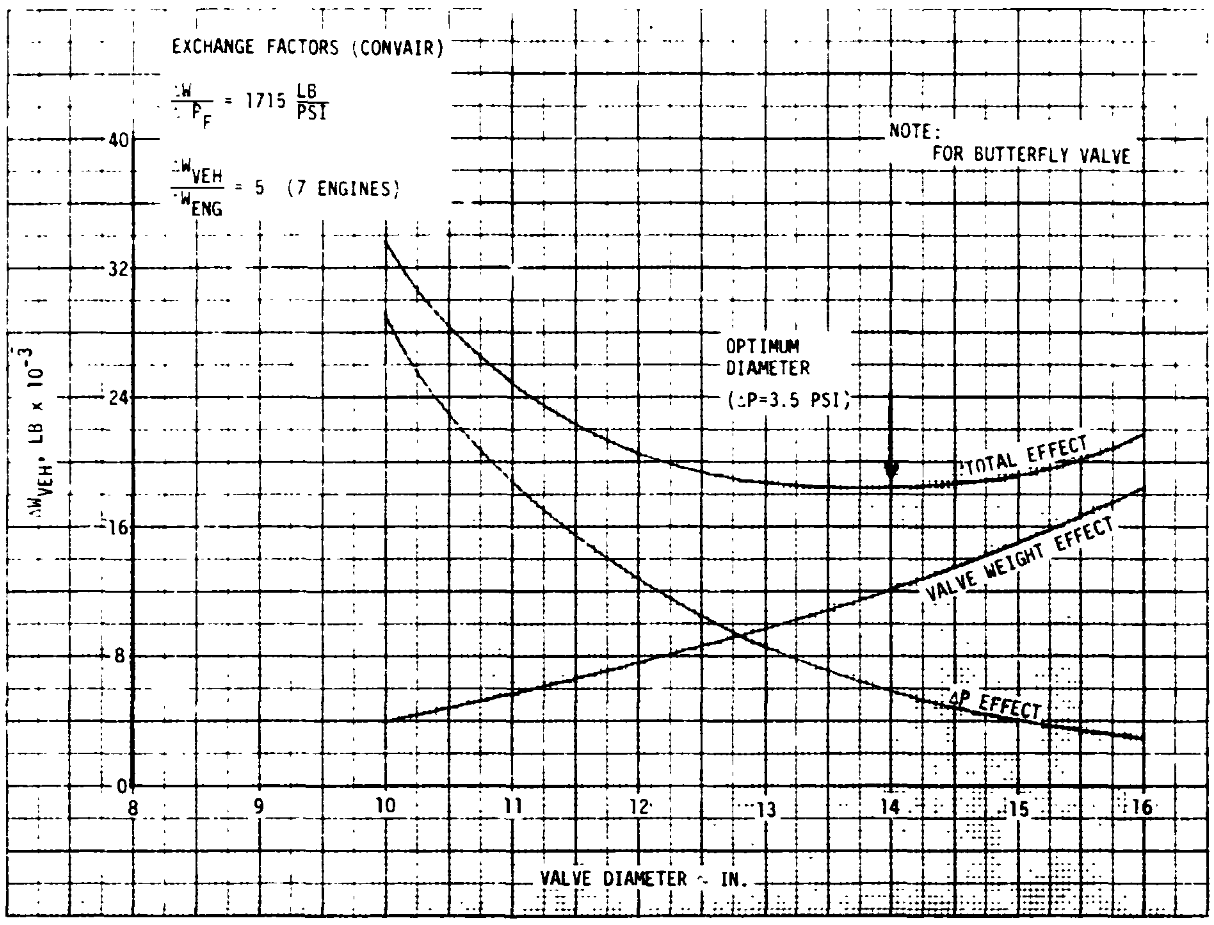


Figure 2.1.3-2. Fuel Valve Diameter Optimization for TRW PFE

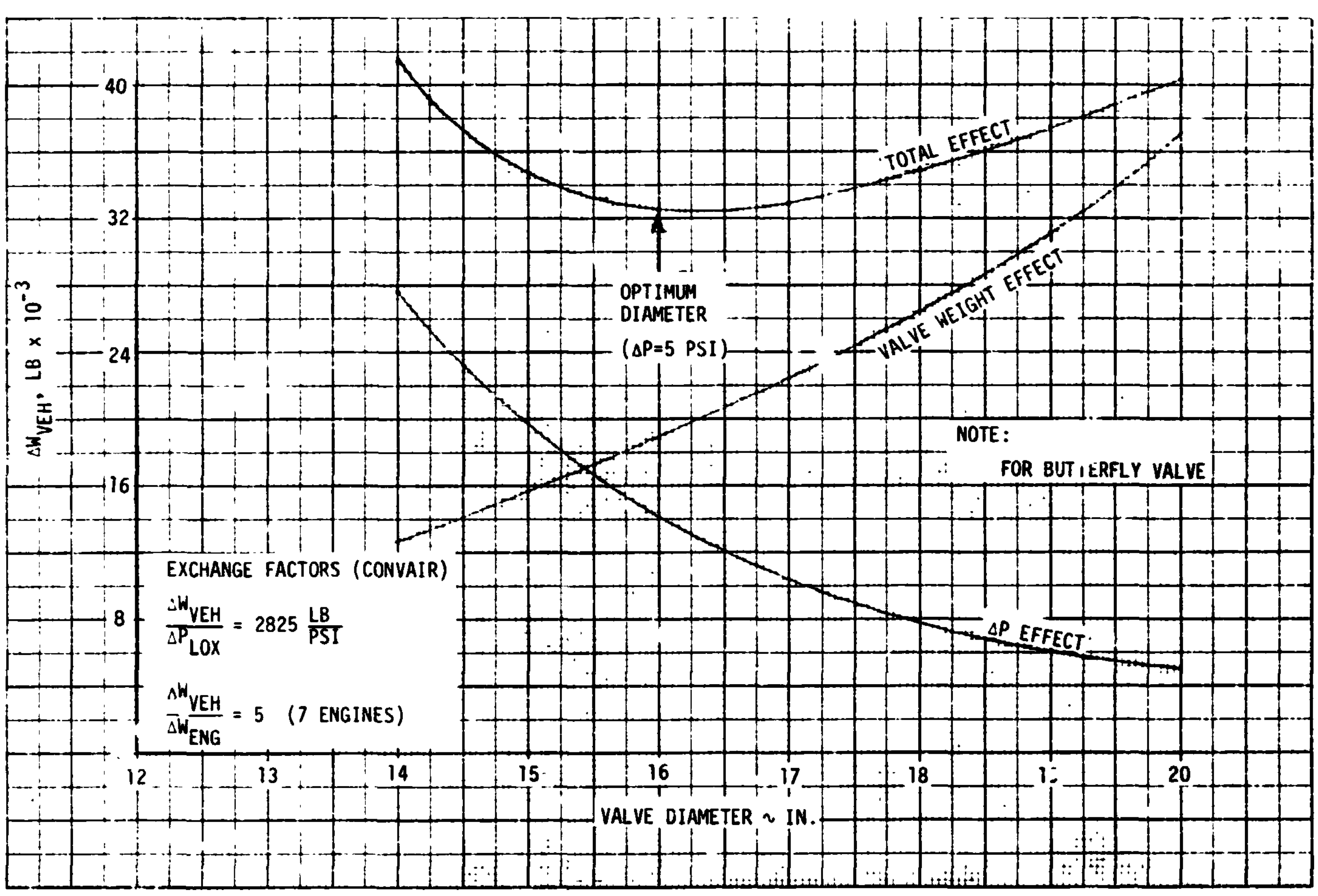


Figure 2.1.3-3. LOX Valve Diameter Optimization

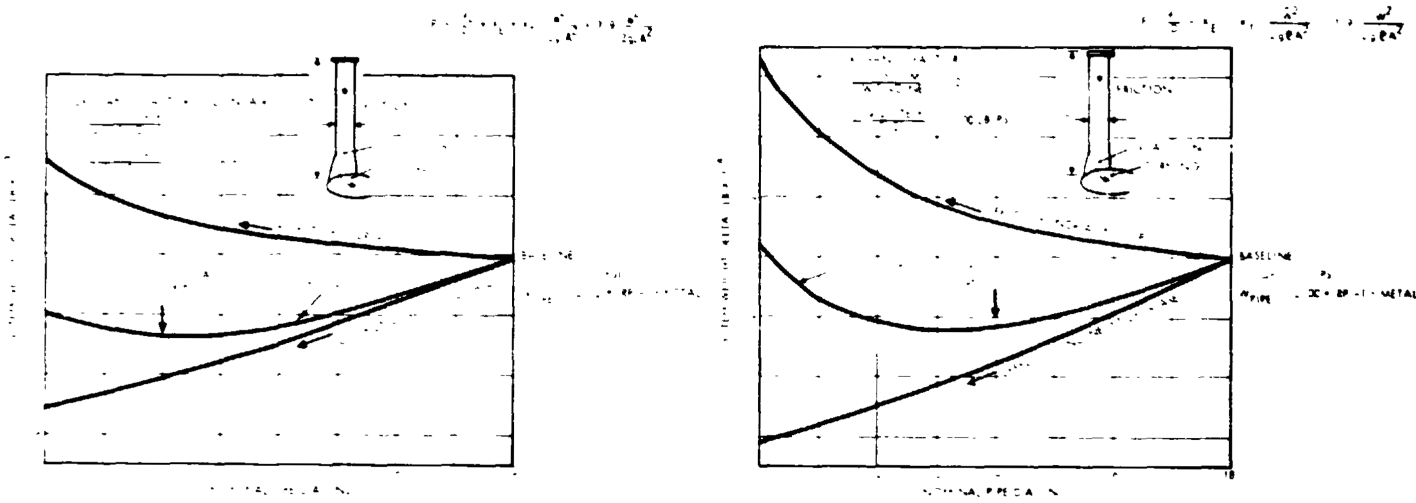


Figure 2.1.3-4. Optimization of Fuel Feed Duct for TRW PFE

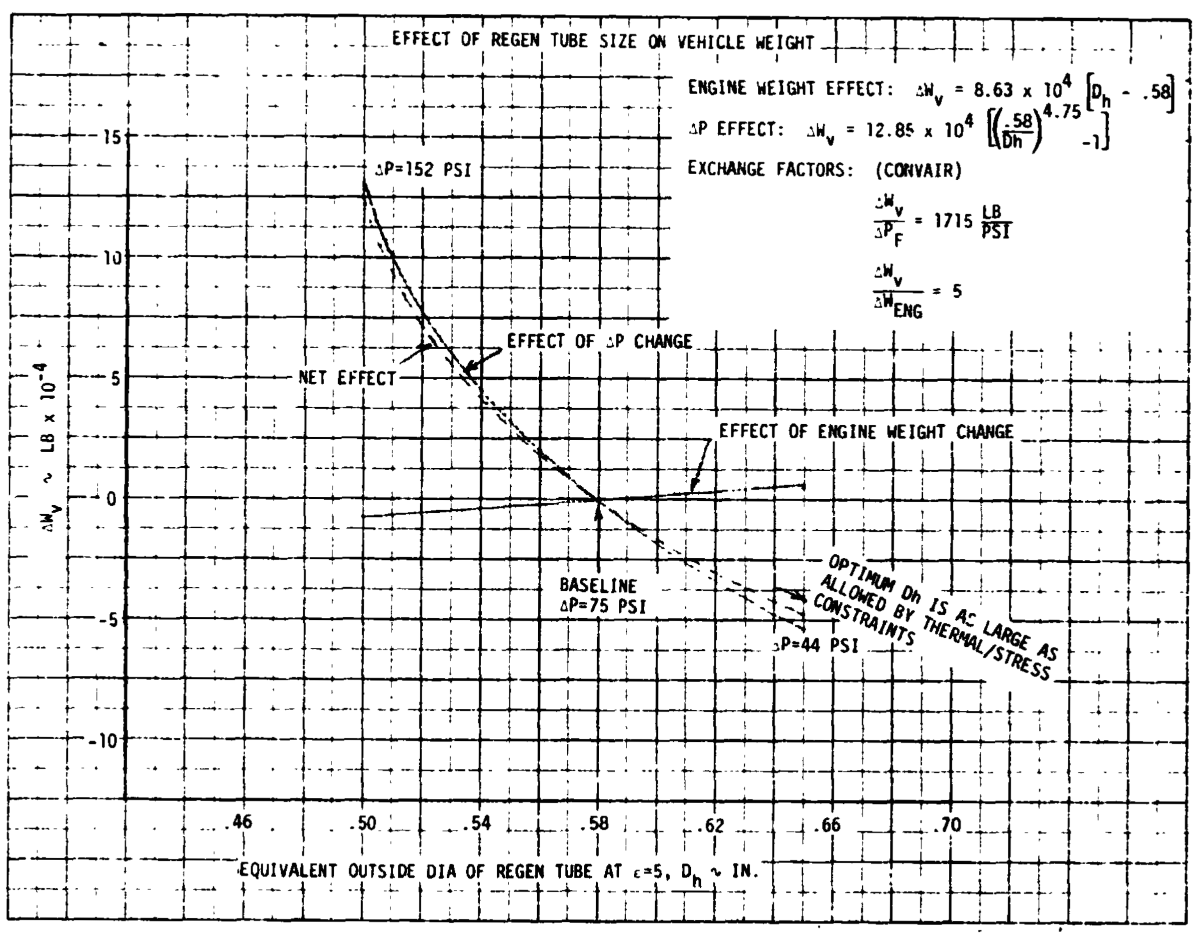


Figure 2.1.3-5. Effect of Regen Tube Size on Vehicle Weight

optimization using two sets of exchange factors was evaluated for the supply duct. The optimum diameter is nearly the same for either set of exchange factors, which differ considerably. Analysis of the effect of regen tube size on vehicle weight indicates that the optimum hydraulic diameter is as large as allowed by thermal and stress constraints. Minimizing regen tube pressure drop is the dominating factor in size optimization of the regen tubes.

Fuel side pressure distribution through the supply duct, toroid, regen tubes, injector inlet and injection annulus is tabulated in Figure 2.1.3-6. The pressure budget for the candidate PFE is presented in Figure 2.1.3-7.

2.1.4 Thrust Vector Control

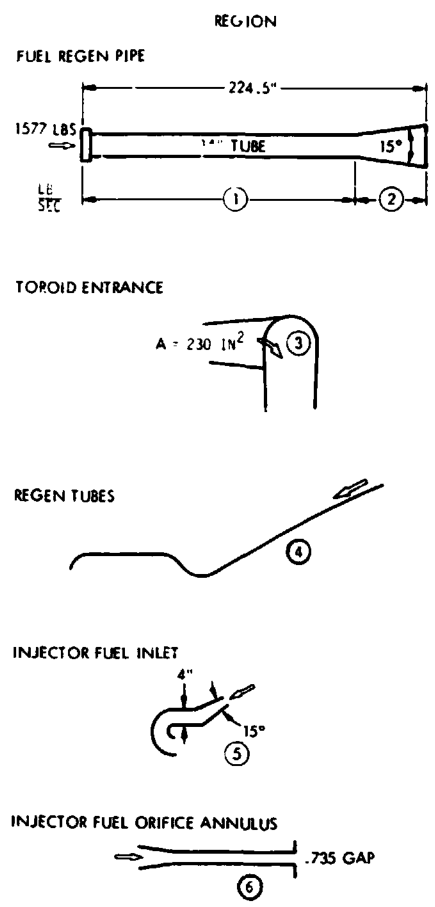
2.1.4.1 Head End Mechanical Gimballing

The baseline engine approach utilizes head end mechanical gimballing.

A detailed approach to the head end gimbal ring is shown in Figure 2.1.4.1-1. It incorporates a large but conventional structured ring with spherical bearing pivots. The spherical bearings are the fabroid surfaced bearings which have clearly demonstrated excellent service with low friction over very long life spans. This approach blends well with the coaxial pintle injector allowing the use of a single oxidizer bellows located inside the ring on the axis of the engine. Two fuel bellows are required for articulation and are located outside the ring on the axis of two adjacent pivot points. The fuel line between the bellows is fixed to the gimbal ring. An external restraining device to prevent bellows extension due to pressure is provided for each fuel bellows; however, the nature of the design eliminates the need for added restraint for the oxidizer bellows. This feature also provides a benefit by reducing structural loads (engine thrust) carried by the gimbal and associated structure by nearly 10%.

2.1.4.2 Secondary Injection Manifolding Into PFE

During the PFE study program, consideration was given to how a secondary injection system could be manifolded to pass the injectant through the primary coolant tube bundle. The results of the effort are shown in



PFE PRESSURE DISTRIBUTION

$$P = \left(\frac{fL}{DA^2} + \frac{K}{A^2}\right)\frac{\dot{w}^2}{2g}$$

Type of Loss	P (PSI)
1. Friction, $\frac{fL}{D}$ = .14	0.72
2. Expansion, K = .25	1.26
3. Turning, K = 1.5	3.1
4. Friction	69.0
5. Expansion (K = .25) Turning (K = 2.2)	1.4
6. Friction + Expansion, C_D = 0.90	40.0

Figure 2.1.3-6. Fuel Side Pressure Distribution

PFE PRESSURE BUDGET
REGENERATIVELY COOLED ENGINE

Location	Liquid Oxygen ΔP, psi	RP-1 ΔP, psi
Control Valve	5.0	3.5
Regen Inlet Duct	---	2.0
Regen Feed Manifold	---	3.1
Regen Tubes	---	69.0
Injector Manifold	---	1.4
Injector Metering Gap	90.0	40.0
Stagnation Press Loss	12.0	12.0
Total ΔP	107.0	131.0
Nozzle Stagnation Pressure (psia)	250.0	250.0
Supply Pressure (psia)	357.0	381

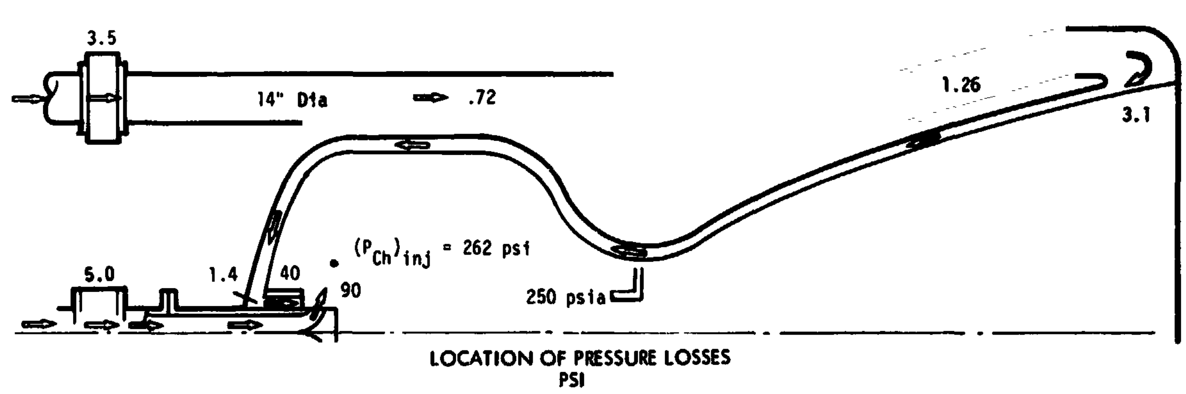
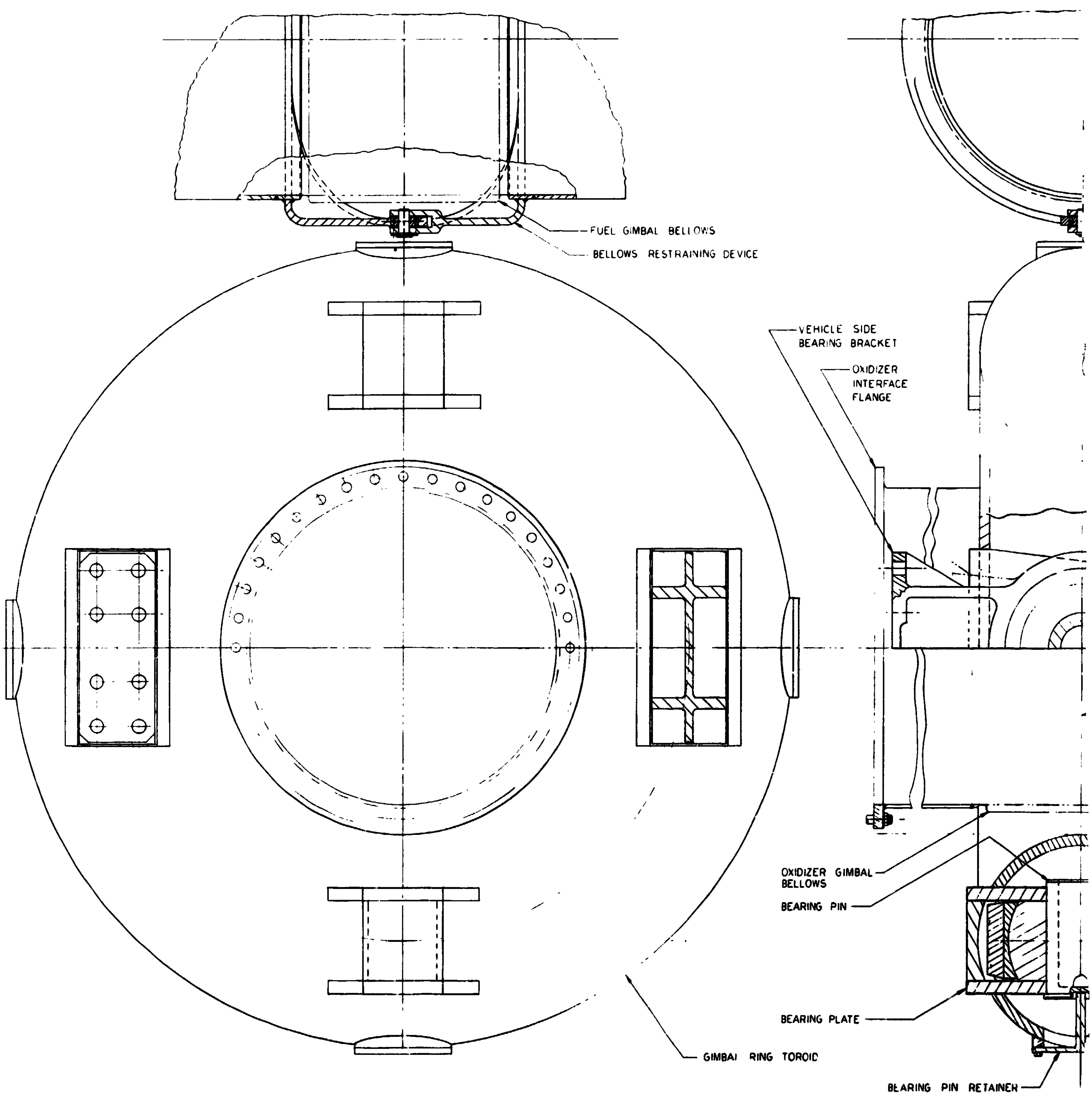


Figure 2.1.3-7. PFE Pressure Budget — Regeneratively Cooled Engine

FOLDOUT FRAME 1



FOLDOUT FRAME 2

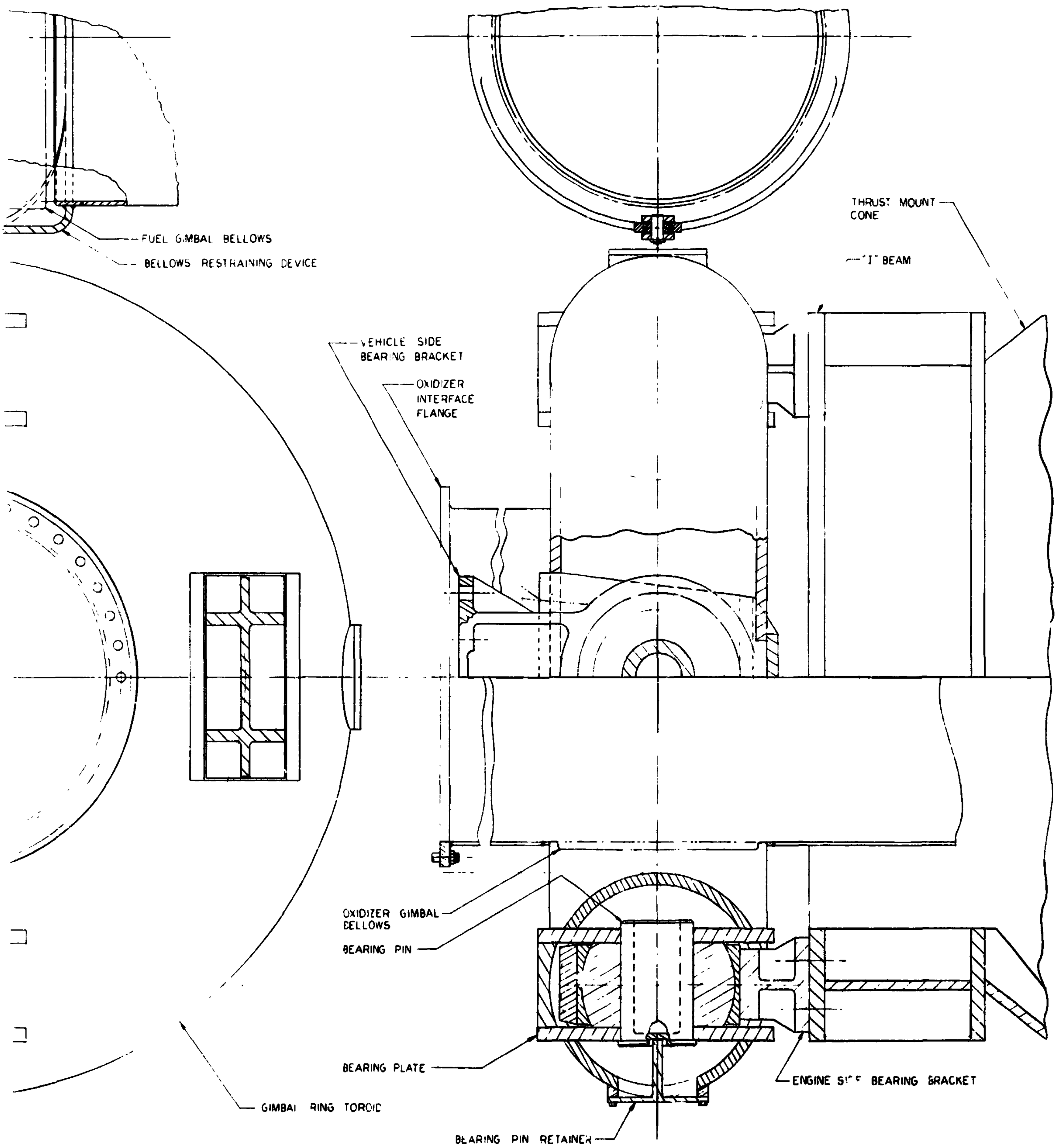


Figure 2.1.4.1-1. Gimbal System for Candidate PFE

Figure 2.1.4.2-1. The primary coolant tube bundle is itself manifolded in the area of the secondary injectant valves. The exit plane to manifold coolant tubes are terminated in this secondary fuel manifold which is continuous circumferentially about the nozzle and extends for about four inches along the nozzle. Fuel manifold to injector tubes pick up the coolant fuel at the manifold and then carry it to the injector. The circumferential fuel manifold is machined on the outside to accept the secondary injection valves. Ports through the manifold carry the secondary injectant flow into the hot gas stream within the nozzle. The continuous manifold approach allows for increased nozzle stiffening, and it eliminates a troublesome feed passage problem for the coolant and the cooling of the SITVC ports.

2.1.4.3 Swivel Nozzle

An approach to thrust vector control which shows great promise is to pivot only the nozzle about a point slightly downstream of the throat. The combustion chamber and head end would be fixed to the structure.

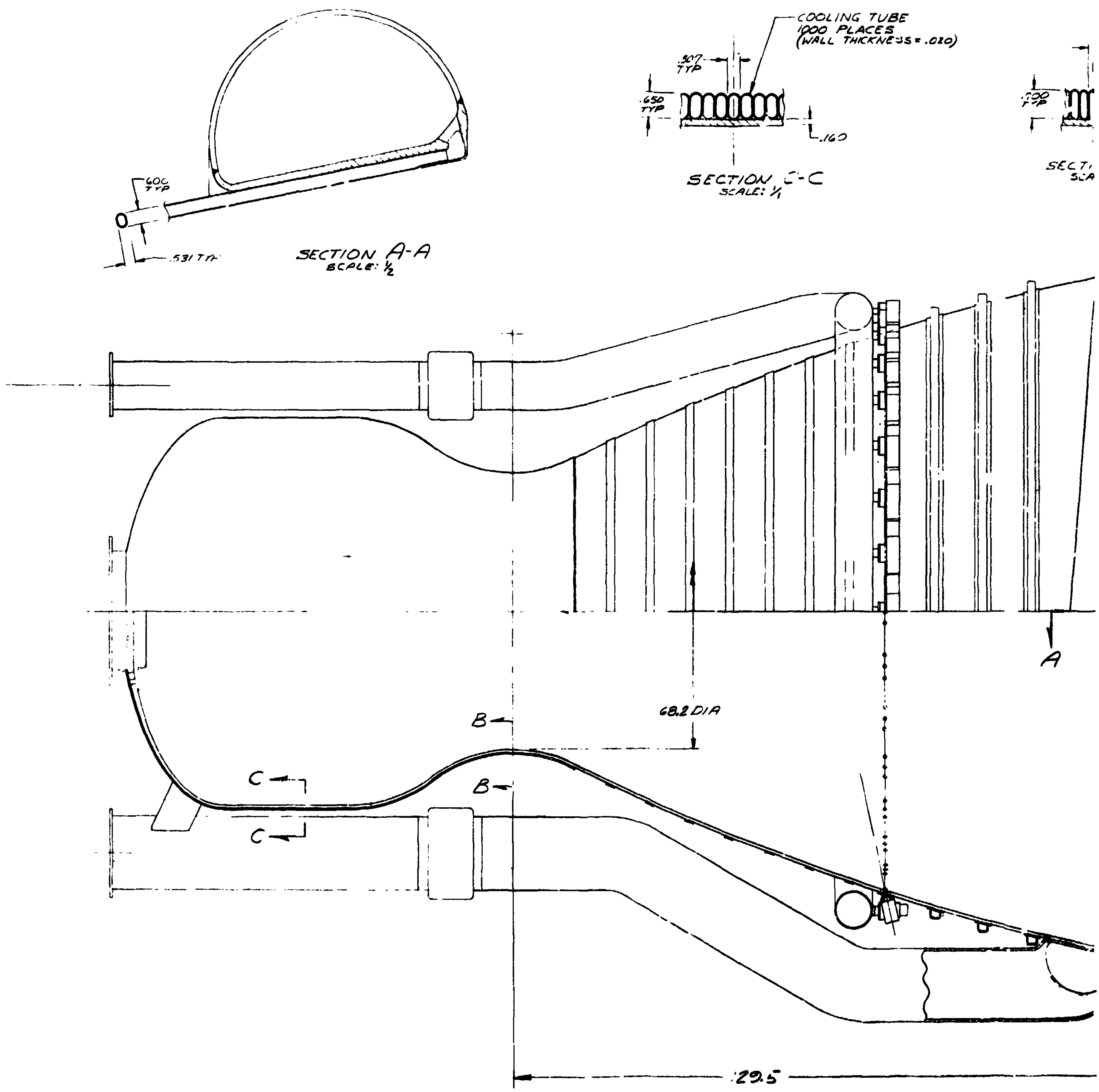
Discussions have been held with United Technology Center regarding the use of the UTC patented Techroll® seal fluid bearing for this application. Although the size of bearing required for this application is many times larger than any yet made, the governing engineering requirement, i.e., unit loading, temperature, angle of deflection, etc., are all well within demonstrated limits for the device. This application is, in fact, far less severe than already demonstrated.

A swivel nozzle using the Techroll® seal is shown in Figure 2.1.4.3-1 for the regenerative and cooled chamber with an ablative nozzle pivoted on the Techroll® seal and actuated by four hydraulic cylinders. The static and dynamic envelopes are also indicated in Figure 2.1.4.3-1. The nozzle being ablative, is consumed and needs replacing after each flight and, therefore, does not need protection against water impact. The fluid bearing readily lends itself to a frangible joint.

This approach offers the following advantages:

- It eliminates the need for either large, relatively high pressure bellows or a secondary injection manifold combined with the regen cooling tube bundle.

FOLDOUT FRAME



FOLDOUT FRAME 2

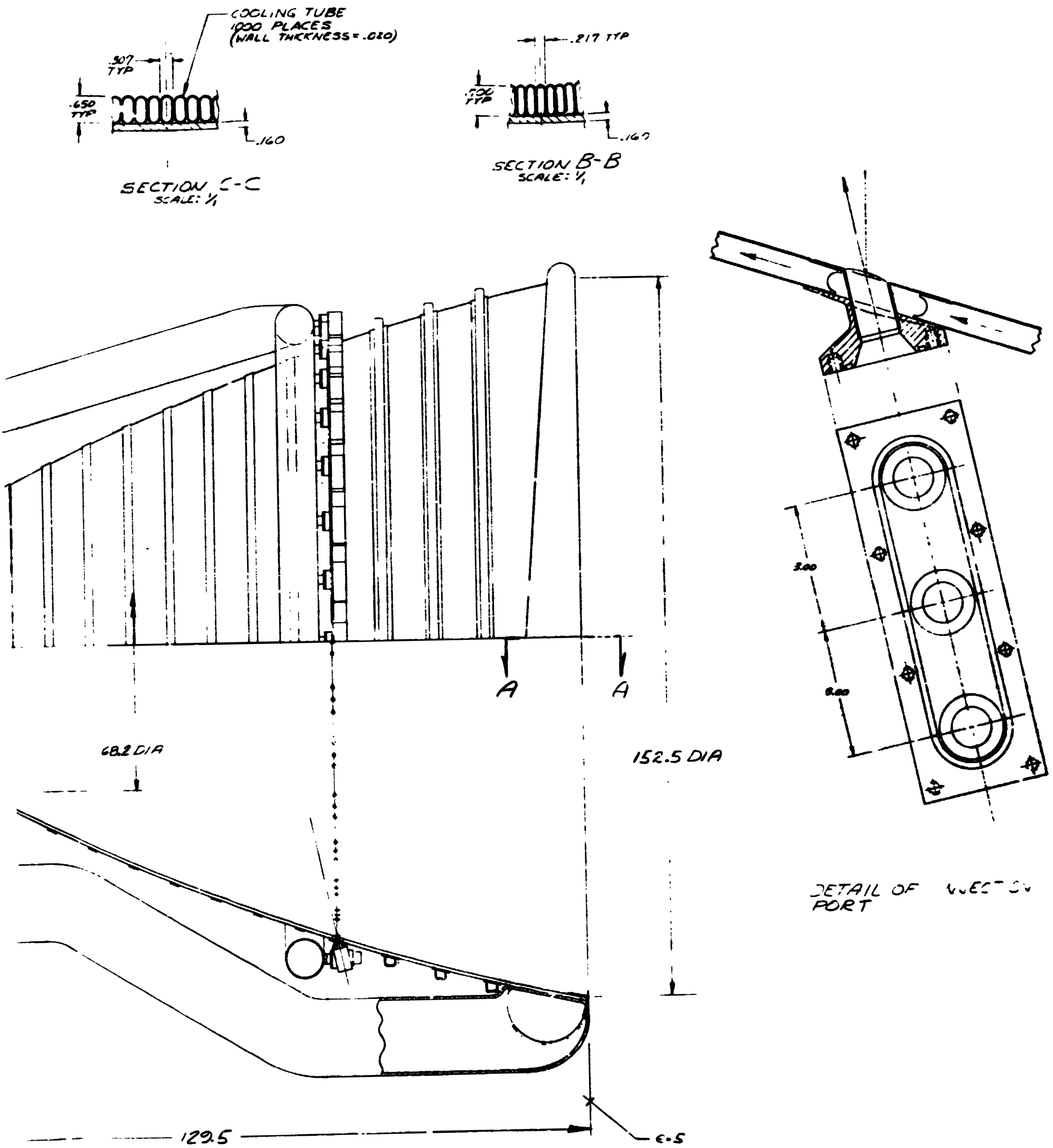


Figure 2.1.4.2-1. **Candidate Regeneratively Cooled PFE with SITVC — 1200K**

- The cooling requirements are substantially reduced in that only the chamber walls and throat require coolant.
- Using duct cooling reduces the required fuel tank pressure on the order of 60 psi.
- Engine weight is reduced by 1500 to 2000 pounds.
- No increase in vehicle diameter in the boattail is required for a boattail to engine expansion ratio of 2.
- Approximately 10,000 pounds of nozzle protective structure is eliminated for each engine.
- The horsepower requirement for gimballing is reduced by approximately 67%.

2.1.5 Ignition Concept

The igniter concept selected is a TEA hypergolic slug (Triethylaluminum) because of its proven reliability. The TEA is stored in a cartridge with burst diagrams at either end, which is closely coupled to the injector, Figure 2.1.5-1. The cartridge outlet is ported to a small volume manifold which supplies twelve 0.1 inch diameter orifices spaced around the pintle. The twelve streams of TEA impinge on 12 of the 36 primary oxidizer streams. Thus, the TEA contacts the LOX very close to the injection ori-

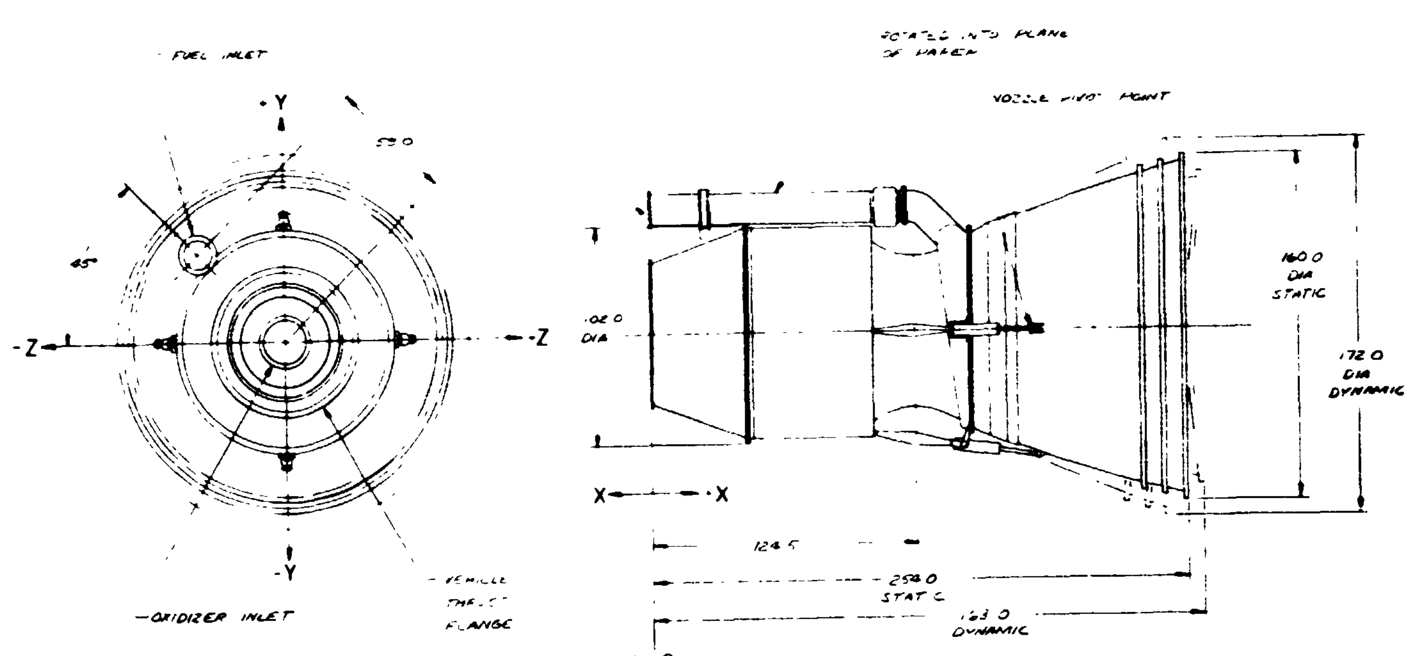
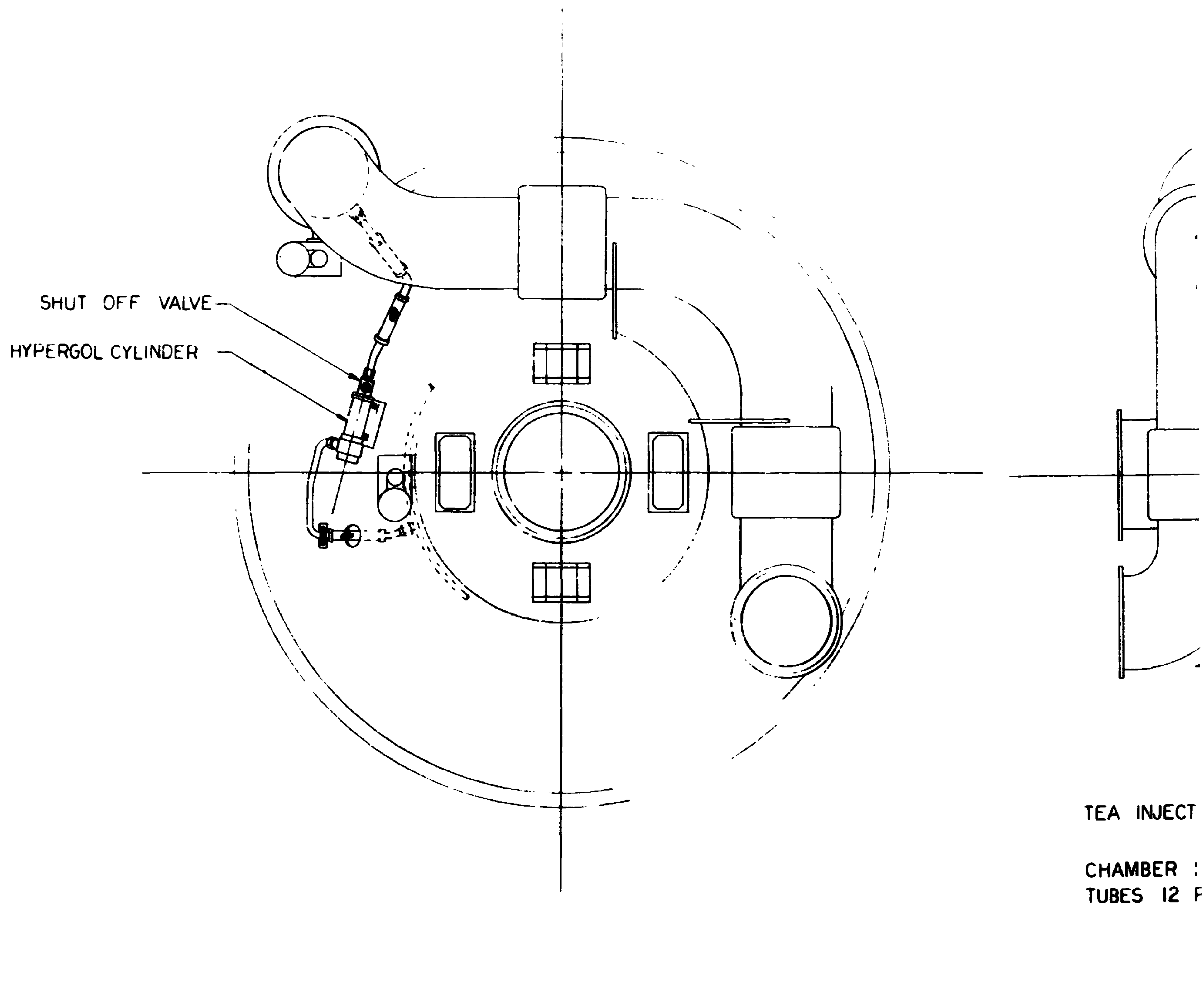


Figure 2.1.4.3-1. Regenerative Chamber with Techroll® Seal Nozzle

FOLDOUT FRAME 1



FOLDOUT FRAME 2

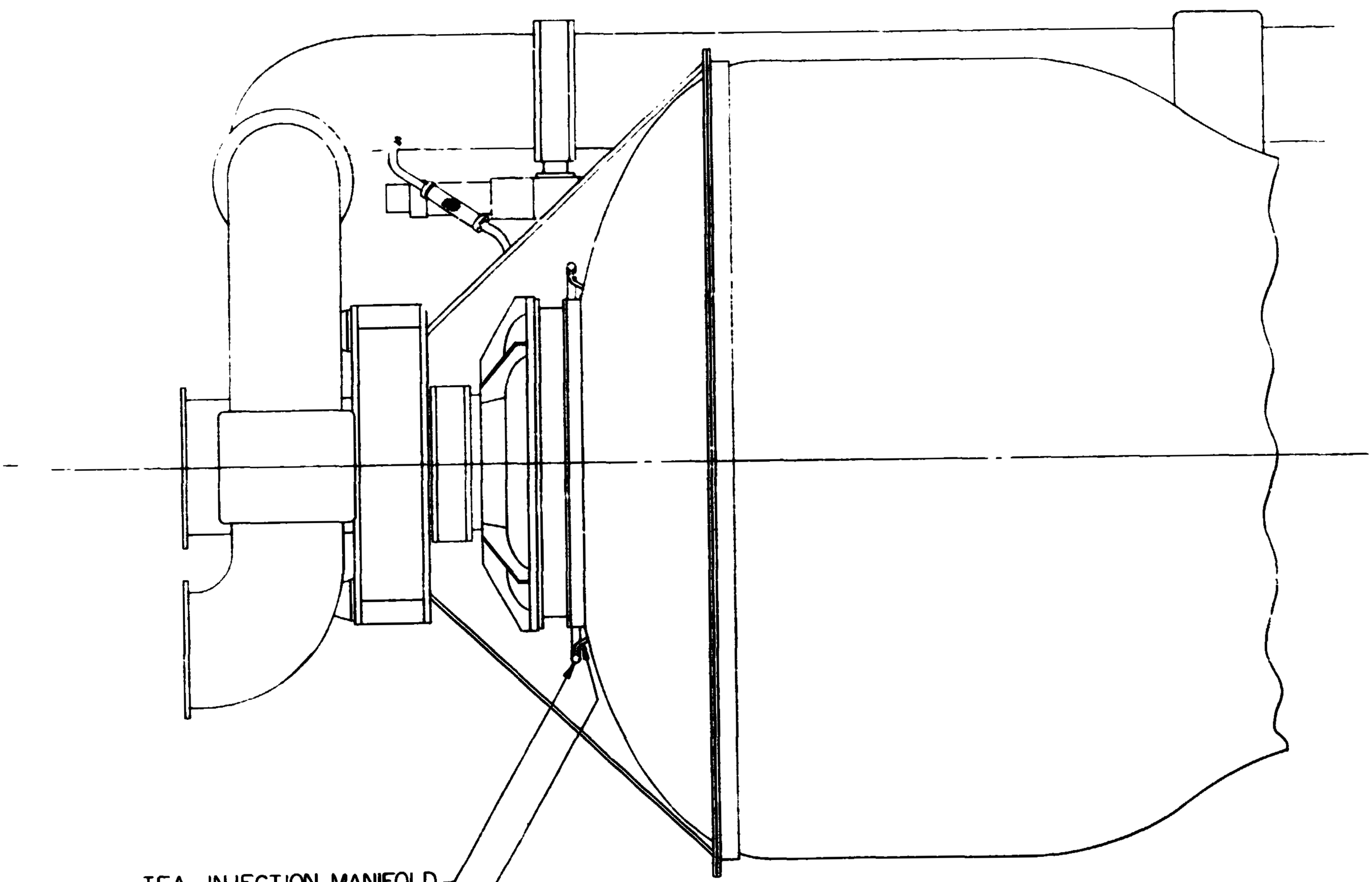


Figure 2.1.5-1. Hypergolic Igniter Configuration

fice outlets, minimizing the volume of LOX accumulated in the chamber prior to ignition. The TEA shut-off valve, integral with the cartridge, is sequenced open at start of opening of the engine LOX valve. The inlet port of the TEA cartridge is supplied with fuel from the main fuel line upstream of the engine fuel valve. The burst discs are actuated by the fuel pressure. After the TEA is expelled from the cartridge and manifold, fuel continues to flow through the TEA injection ports, entering into the mixing and combustion process. Total volume of the TEA manifolding is 30 in^3. The TEA is expelled in less than 1 second.

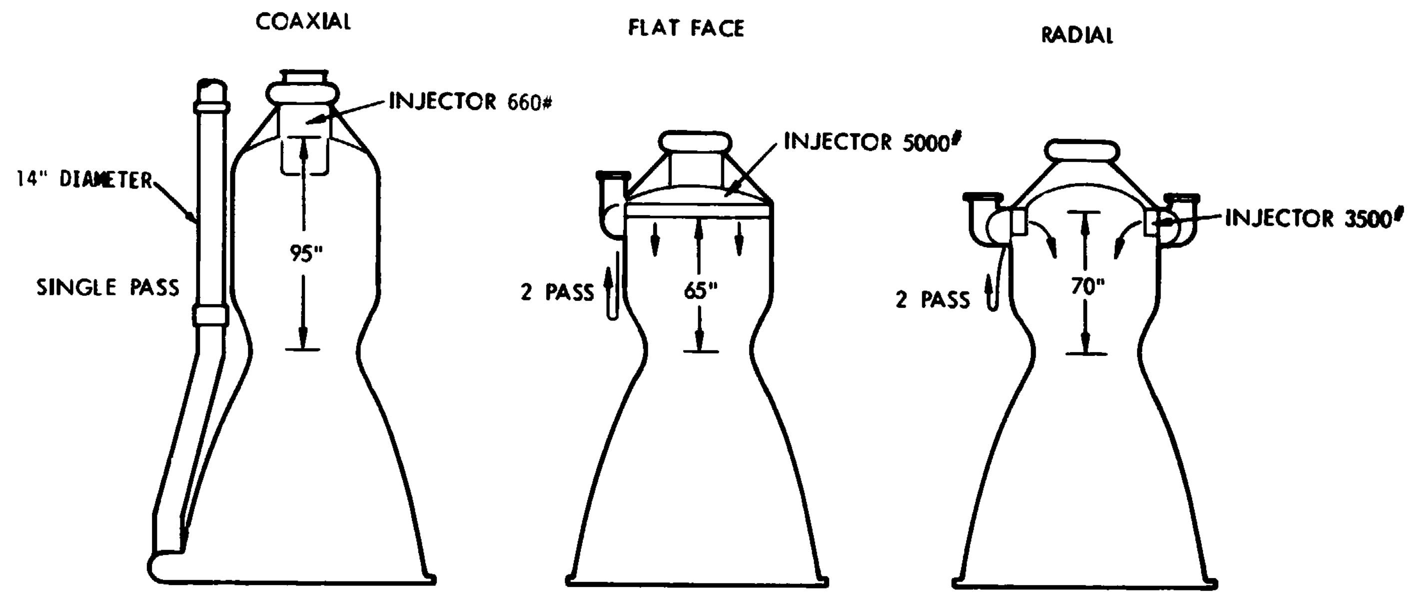
2.1.6 Affect of Injection/Thrust Chamber Selection

The TRW PFE utilizes a single pass cooling approach. At first glance it appears that the use of a two pass cooling scheme would result in an optimal PFE. However, a total system interaction analysis reveals this is not the case. In addition, the higher ΔP requirements in the pintle injector would appear to be adverse. A detailed analysis was conducted to determine the nature of these effects.

The affect on vehicle weight of three different types of injectors is compared in Figure 2.1.6-1. The injectors compared are the coaxial, flat plate, and radial types. Included in the comparison are differences in chamber length associated with the different injectors. Additionally, two pass regenerative cooling of the chamber is assumed with the flat face and radial injectors. The affect on vehicle weight is presented for two different sets of exchange factors. The results of the analysis insure that the coaxial injector, even with a longer chamber length and higher LOX supply pressure requirements, will result in the lightest vehicle weight because of the low weight of the coaxial injector and the use of the single pass cooling concept.

2.1.7 Mass Properties

Detailed weights data as a function of thrust were generated during the PFE study for both the gimballed and LITVC regeneratively cooled engines. In addition, weights data for duct cooled and swivel nozzle configurations were generated for a 1200K thrust engine. These weights data are presented in the following tables.



SINGLE ENGINE WEIGHTS, LBS

INJECTOR TYPE	COAXIAL	FLAT FACE	RADIAL INJECTION
DRY	11,467	14,607	13,229
WET	14,956	16,864	15,507

CHANGE IN POUNDS IN BOOSTER WEIGHT AS A FUNCTION OF:

INJECTOR TYPE	COAXIAL	FLAT FACE		RADIAL INJECTION	
Propellant loading ratio		λ = .85 (2)	λ = .89 (2)	λ = .85	λ = .89
Engine weight	Baseline	160,000	66,800	46,300	19,300
Nominal engine pressure drops (1)	Baseline	0	-44,300	0	-44,300
TOTAL EFFECT		160,000	22,500	46,300	-25,000
Addition of 10 psi to nominal engine pressure drops to flat face and radial injectors	Baseline	144,000	45,300	144,000	45,300
TOTAL EFFECT		304,000	67,800	190,300	20,300

(1) NOMINAL PRESSURE DROPS

INJECTOR TYPE	FUEL INJECTOR DROP, PSI	OXIDIZER INJECTOR DROP, PSI	REGENERATIVE JACKET DROP, PSI
COAXIAL	40	90	60
FLAT FACE	50	50	50
RADIAL	50	50	50

(2) EXCHANGE RATIOS

	λ = .85	λ = .89
Δ (tank + propel wt) / Δ (all engine wts)	12	5
Δ (tank + propel wt) / Δ (pressure drop)	7200	Lox 2825 RP 1715

Figure 2.1.6-1. Engine Type Weight Comparison

1200K Regen Engine System Weight vs. Contraction Ratio
(Gimbal Actuators and APU System not included)

	CONTRACTION RATIO =	2	3	4
1.	Shutoff Valves	980	980	980
2.	Injector Element	660	660	660
3.	Fuel Manifold and Duct	676	676	676
4.	Head End Shell	755	1,320	2,040
5.	Head Tubes	411	458	517
6.	Combustion Chamber Shell	1,759	2,611	3,515
7.	Combustion Chamber Tubes	1,326	1,321	1,373
8.	Nozzle Bands	370	370	370
9.	Nozzle Tubes	1,054	1,054	1,054
10.	Gimbal Assembly	1,676	1,676	1,676
11.	Gimbal Support Structure	1,400	1,400	1,400
12.	Integration Hardware	400	400	400
	Dry Weight, Gimballed	11,467	12,926	14,661
13.	Residual Fuel	3,152	3,205	3,259
14.	Residual Oxidizer	337	337	337
	Wet Weight, Gimballed	14,956	16,468	18,257
	Dry Weight, LITVC	11,561	13,020	14,755
	Wet Weight, LITVC	16,175	17,687	19,476

Regenerative Engine System Weight vs. Thrust
(Gimbal Actuators and APU System not included)

	Item	600K	900K	1200K	1400K
1	Shutoff Valves	368	660	980	1230
2.	Injector Element	275	460	660	804
3.	Fuel Manifold and Duct	240	440	676	851
4.	Head End Shell	267	490	755	954
5.	Head Tubes	216	309	411	480
6.	Combustion Chamber Shell	623	1,141	1,759	2,220
7.	Combustion Chamber Tubes	663	995	1,326	1,548
8.	Nozzle Bands	131	240	370	467
9.	Nozzle Tubes	527	791	1,054	1,230
10.	Gimbal Assembly	419	942	1,676	2,280
11.	Gimbal Support Structure	495	910	1,400	1,768
12.	Integration Hardware	200	300	400	466
	Dry Weight, Gimballed	4,424	7,673	11,467	14,298
13.	Residual Fuel	1,120	2,050	3,152	3,980
14.	Residual Oxidizer	120	219	337	425
	Wet Weight, Gimballed	5,664	9,947	14,956	18,703

LITVC Regenerative Engine System Weight

	Item	600K	900K	1200K	1400K
1.	Shutoff Valves	368	660	980	1,230
2.	Injector Element	275	460	660	804
3.	Fuel Manifold and Duct	240	440	675	851
4.	Heat End Shell	267	490	755	954
5.	Head Tubes	216	309	411	480
6.	Combustion Chamber Shell	623	1,141	1,759	2,220
7.	Combustion Chamber Tubes	663	995	1,326	1,548
8.	Nozzle Band	259	638	1,070	1,452
9.	Nozzle Tubes	527	791	1,054	1,230
10.	Integration Hardware	200	300	400	466
11.	Engine Support Structure	283	530	800	1,010
12.	LITVC Ducts and Valves for 5° Equivalent	539	1,036	1,670	2,055
	Dry Weight, LITVC	4,460	7,790	11,561	14,300
13.	Residual Fuel	1,177	1,870	2,859	3,580
14.	Residual Oxidizer	723	1,140	1,755	2,220
	Wet Weight, LITVC	6360	10,800	16,175	20,100

1200K Gimbaled Regenerative Chamber with Ablative Techroll Nozzle ($\epsilon = 5$)

	Item	Weight, LB
1.	Shutoff Valves	980
2.	Injector Element	660
3.	Fuel Manifold and Duct	421
4.	Head End Shell	755
5.	Head Tubes	411
6.	Combustion Chamber Shell	1,759
7.	Combustion Chamber Tubes	1,326
8.	Fixed Engine Support Structure	800
9.	Throat to Nozzle Transition	591
10.	Nozzle	3,636
11.	Nozzle Seal	240
12.	Integration Hardware	400
		11,979
	DRY WEIGHT	
13.	Residual Fuel	1,952
14.	Residual Oxidizer	337
		14,268
	WET WEIGHT	
15.	Actuators (4)	300
16.	APU, Servo Valves	162
		14,730

A summary of the mass properties information for 1200K thrust configurations is presented below:

Configuration	Dry Weight (Pounds)	Wet Weight (Pounds)	Wet Moment of Inertia About Structural Mass ($SL\text{-}FT^2$)	Wet Moment of Inertia of Swiveled Mass ($SL\text{-}FT^2$)
Gimballed	11,467	14,956	50,600	50,600
LITVC	11,561	16,175		
Duct	11,123	11,870		
Swivel	11,979	14,268	49,771	2,480

2.2 MAIN VALVES

A buterfly valve approach was taken for the main valves (Figure 2.2-1). This approach was based upon successful commercial use of this type of valve. Table 2.2-1 summarizes some pertinent experience.

Low Pressure Hydraulic Actuators

As a baseline approach low pressure hydraulic actuation utilizing fuel at tank pressure was assumed. The actuators are sized to a 380 psia source. The method provides a power source of large capacity Vent flow can simply be overboarded into the engine skirt. Figure 2.2-2 provides a schematic of the overall engine valve system.

The approach allows for straightforward design inasmuch as currently available hydraulic cylinder and pilot valve configurations can be utilized requiring no new development of seals and mechanisms.

High Pressure Hydraulic Actuators

The actuating cylinder size can be much reduced and a single stage pilot valve potentially used by use of high pressure hydraulic actuators (3000 psi). Standard high pressure hydraulic components can be used by simplifying development of the system.

If standard pump supplied hydraulic pressure were available it undoubtedly would be the desirable source. Fuel can be utilized by increasing the pressure using a low pressure operated booster as shown schematically in Figure 2.2-3. Fuel at tank pressure is applied to a large diameter double

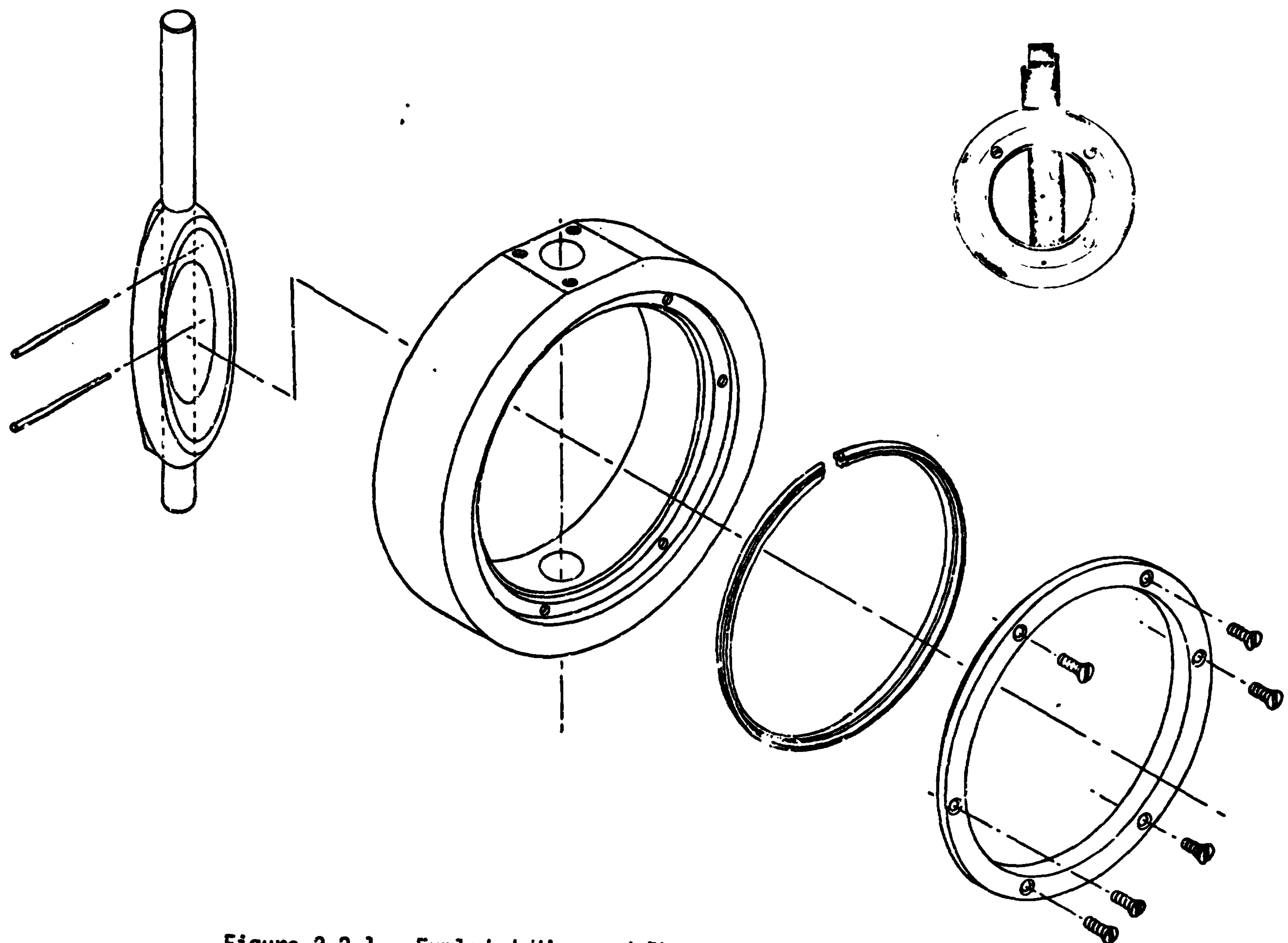


Figure 2.2-1. Exploded View and Photo of Typical Propellant Valve

Table 2.2-1. Typical Current Commercial Valve Applications of the Posi-Seal Design

THE TABLE BELOW REPRESENTS A CROSS SECTION OF APPLICATIONS OF THE POSI-SEAL WAFER TRUNNION VALVE DESIGN ILLUSTRATING THE RANGE OF SIZES, PRESSURES AND OPERATING TEMPERATURES. IN ADDITION TO THE SPECIFIC SIZES NOTED, MANY OTHER APPLICATIONS IN THE 1 TO 24 INCH RANGE ARE IN EXISTENCE WITH A RANGE OF PRESSURES AND TEMPERATURES.

Valve Size (in.)	Medium	Application	Seal Material	Temperature Range	Pressure (psi)	Approximate Cycles (to date)	Approximate Time in Service No Failure or Leakage to Date
8	LNG	Shutoff Valve	KEL-F	Ambient to -258°F	25	30	2-1/2 years
12	LN_2	Shutoff Valve	KEL-F	Ambient to -320°F	600	52	1 year
24	LN_2	Block Valve	KEL-F	Ambient to -320°F	300	750	2 years
16	Water	Test Shutoff Valve	Teflon	Ambient	400	50	1 year
18	Water	Shutoff	Teflon	Ambient	700	3500	3 years
20	Steam	Shutoff	Teflon	+350°F	15	Unknown	1-1/2 years
24	Steam & Hot Gas	Shutoff	Metal	+500°F	700	Unknown	
60	Water	Shutoff	Teflon	Ambient	700	Infrequent	

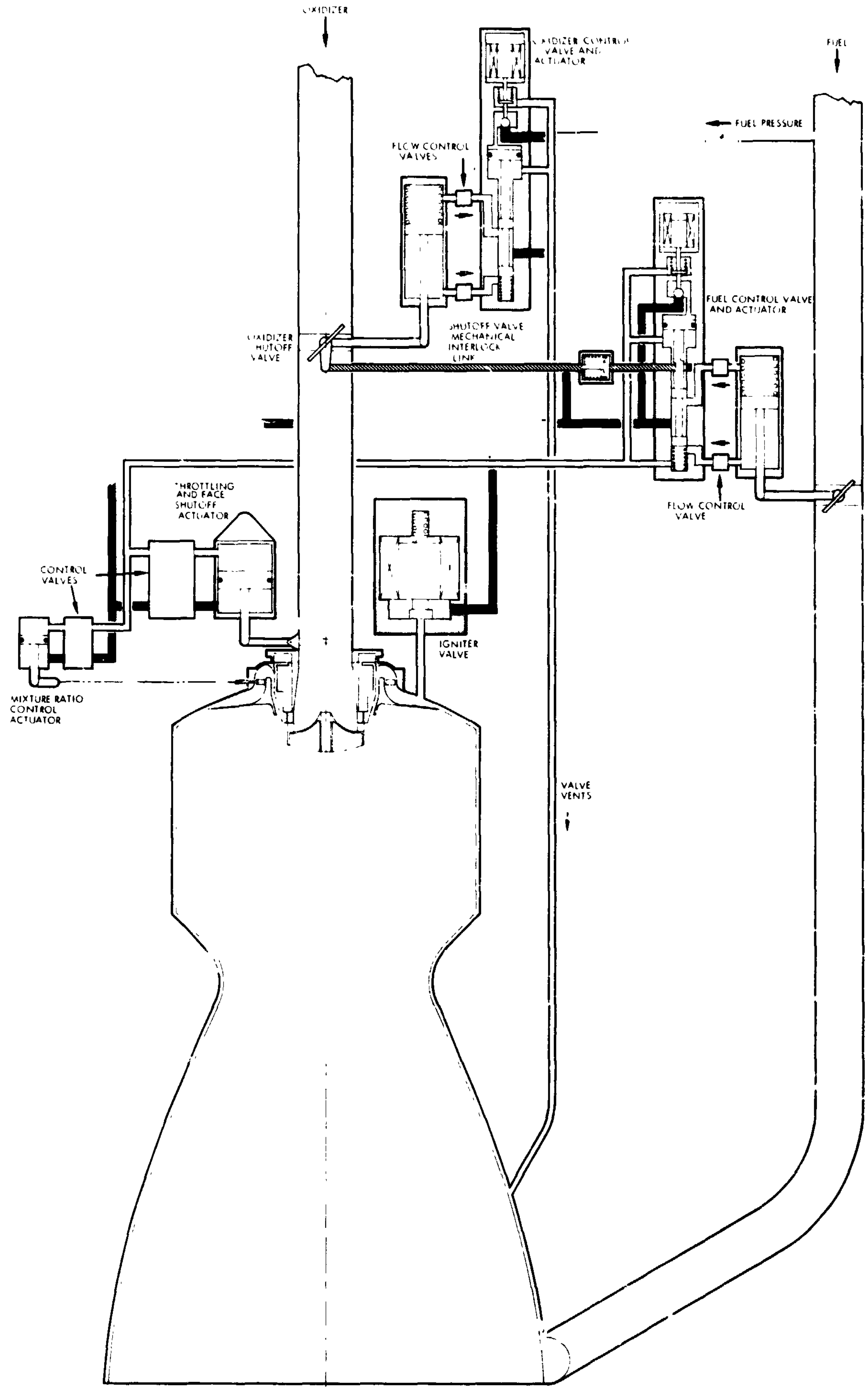


Figure 2.2-2. Engine Hydraulic Schematic

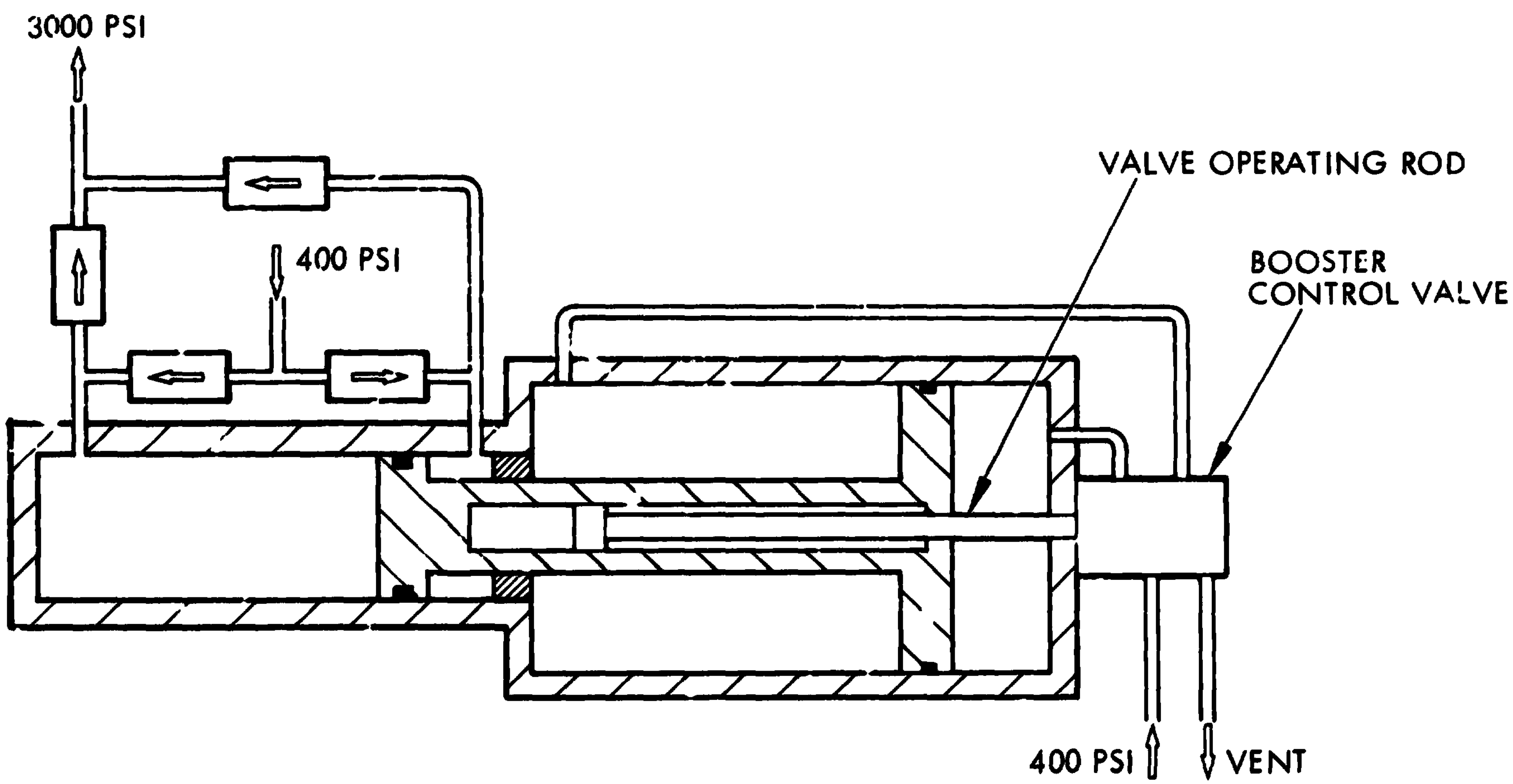


Figure 2.2-3. Fuel Pressure Booster

acting cylinder which then drives a small cylinder increasing the pressure essentially by the ratio of piston areas. Valving can be built in and mechanically actuated. Devices of this type are commercially available for industrial applications.

2.2.1 LITVC Valves

As a result of detailed LITVC studies RP-1 would be recommended as the working fluid due to minimum complexity and therefore highest system reliability and lowest system development risk. A summary of the side specific impulse versus thrust vector angle is presented in Figure 2.2.1-1 for a 5:1 nozzle. The performance calculations were based on multiple orifice injection at an expansion ratio of about 3:1. The resulting injectant weights and volumes per engine are presented in Figures 2.2.1-2 and 2.2.1-3 as a function of total axial impulse and a 1° average deflection angle. The resulting duct and manifold sizes as a function of thrust level are presented in Figure 2.2.1-4. Also shown are the maximum flowrate requirements at the 1.2×10^6 lbf for 5° maximum angle. The RP-1 flowrate at 6° is also indicated. A weight trade-off study was conducted varying the number of values fired at one time and the total number of valves per engine based on an omni-axis control system. The results as presented in Figure 2.2.1-5 indicated that a minimum weight is achievable with various combinations. For a 6° deflection angle using RP-1 the total maximum flowrate is 2100 lbs/sec. Based on a comparison of volumetric flowrates a total of 32 valves should be used firing either 6 or 8 at a time to be able to use the largest currently available servoinjector valve. The recommended approach is to fire 6 valves at a time for optimum performance and enlarge the valves to handle 350 lbs/sec of RP-1 at 380 psia supply pressure.

A typical valve as shown in Figure 2.2.1-6 would have three injector pintles mechanically linked and positioned by a servovalve controlled RP-1 actuator operating off of supply line pressure. The valve should weigh on the order of 12 lbs and have a full stroke response of about 0.[illegible] second to provide the 10 deg/sec slewrate.

2.3 CONTROLS

The engine includes the following design features:

1. Butterfly type shutoff valves including high pressure RP-1 actuators.

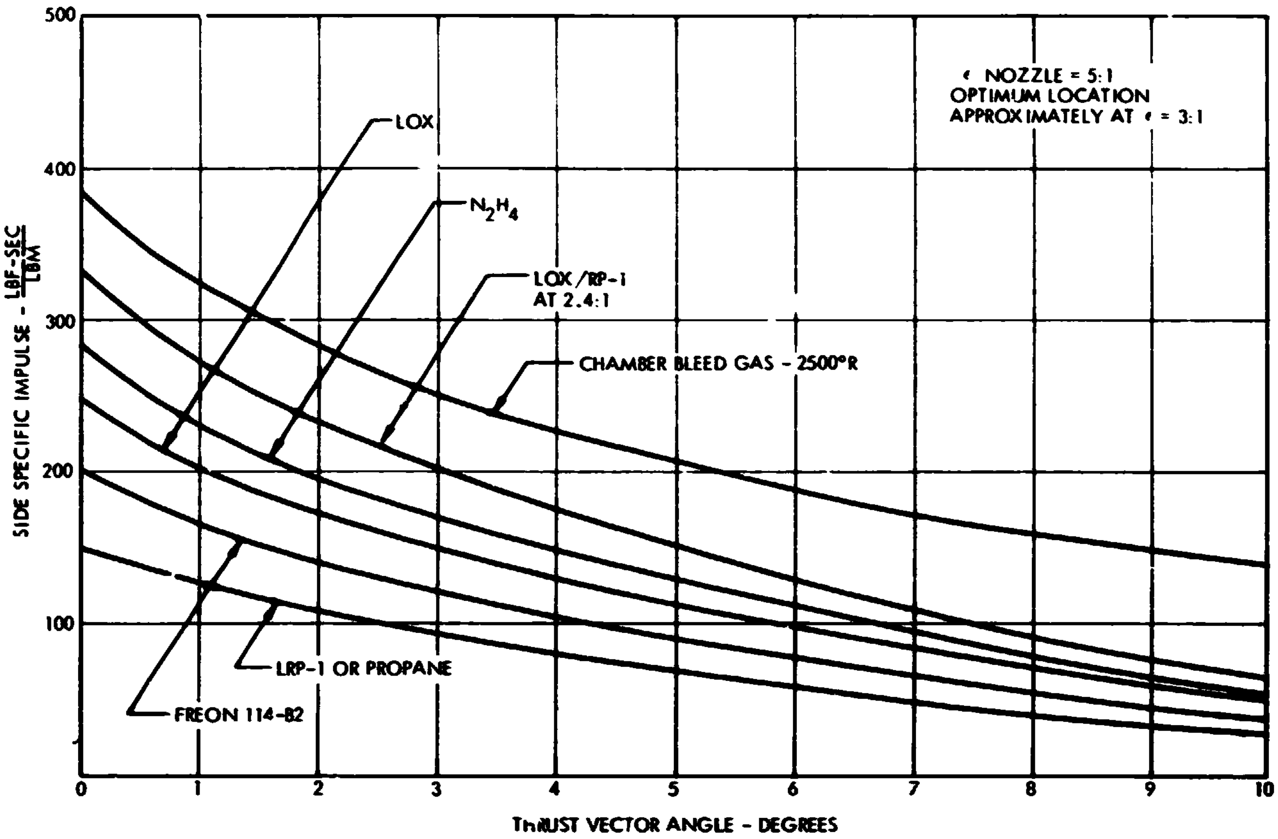


Figure 2.2.1-1. [illegible]iple Orifice Side Specific Impulse vs. Deflection Angle

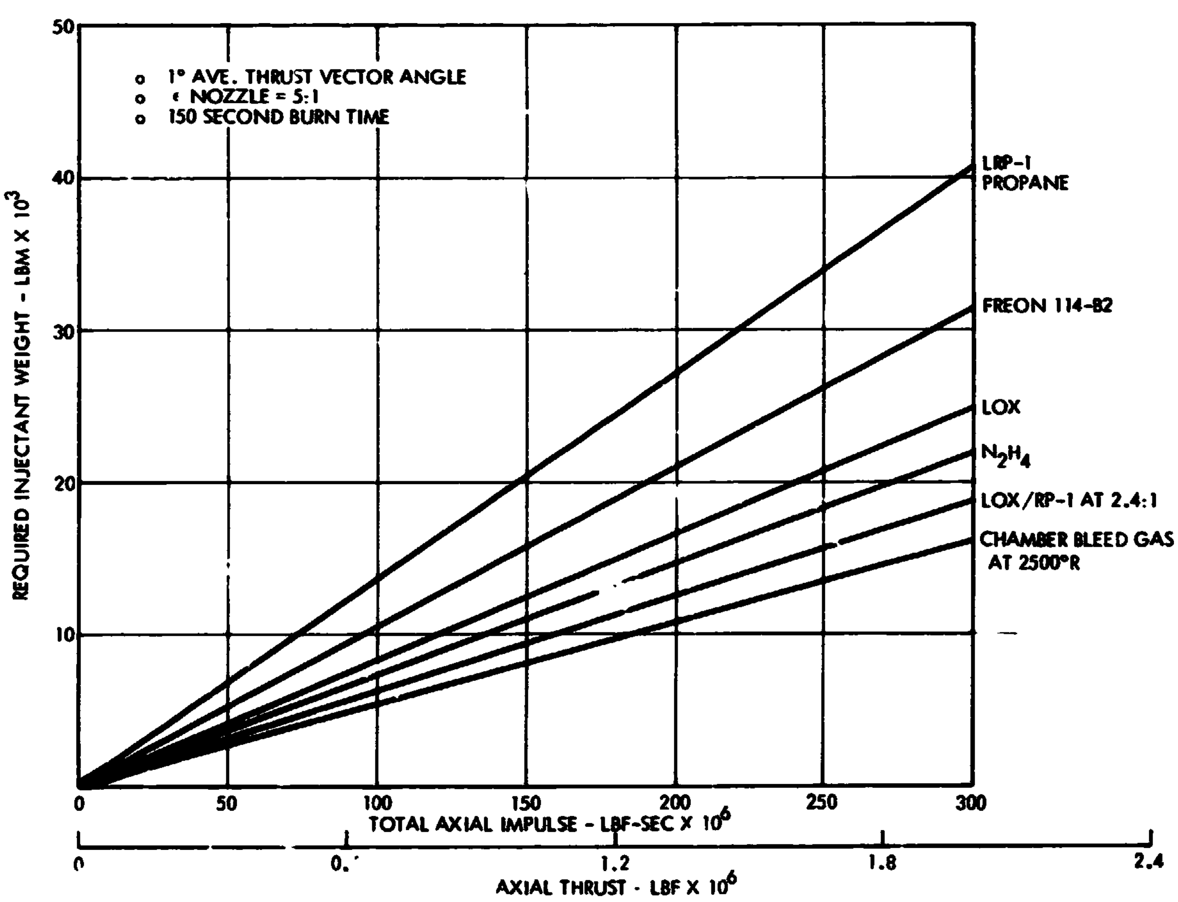


Figure 2.2.1-2. LITVC Injectant Weight vs. Axial Impulse per Engine

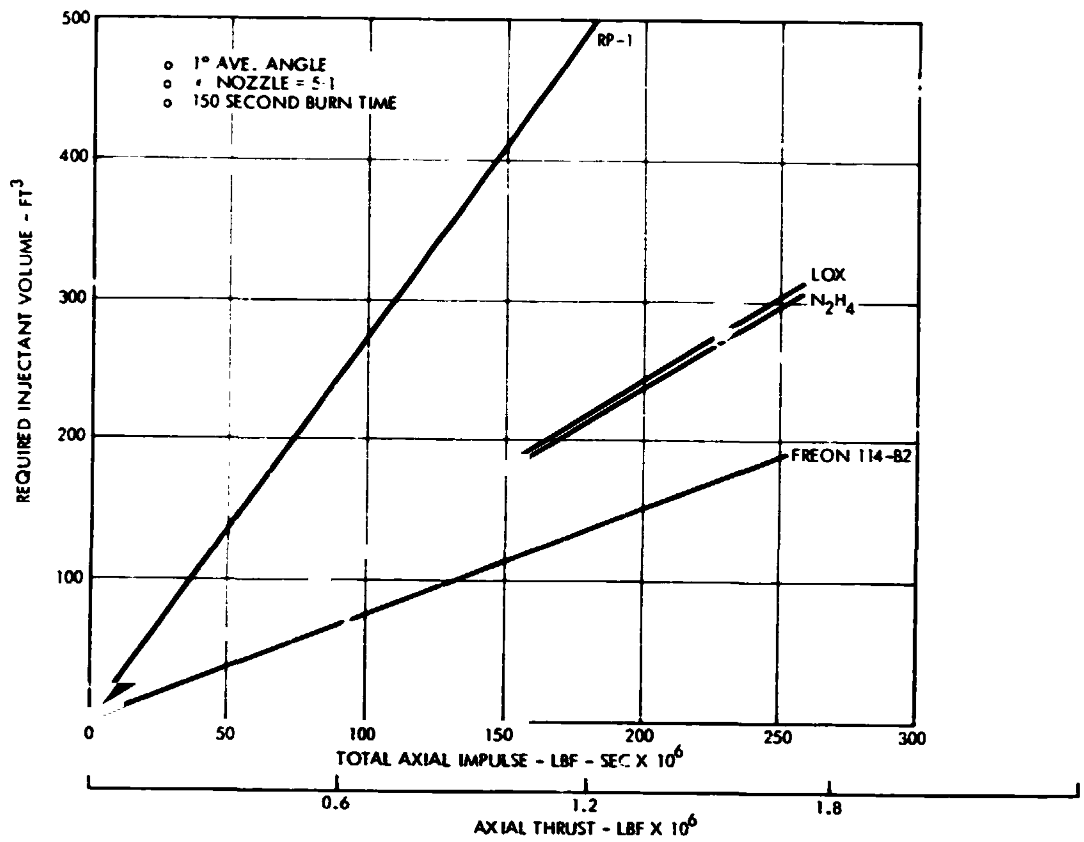


Figure 2.2.1-3. LITVC Injectant Volume vs. Axial Impulse per Engine

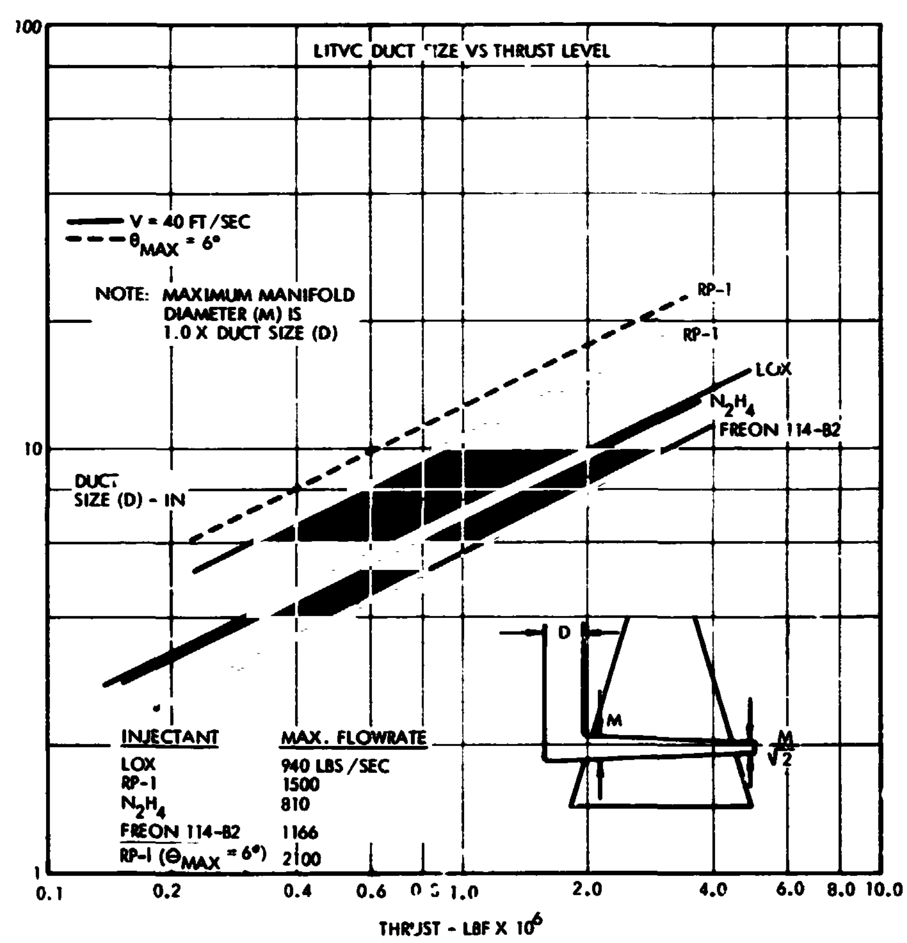


Figure 2.2.1-4. LITVC Duct Size vs. Thrust Level

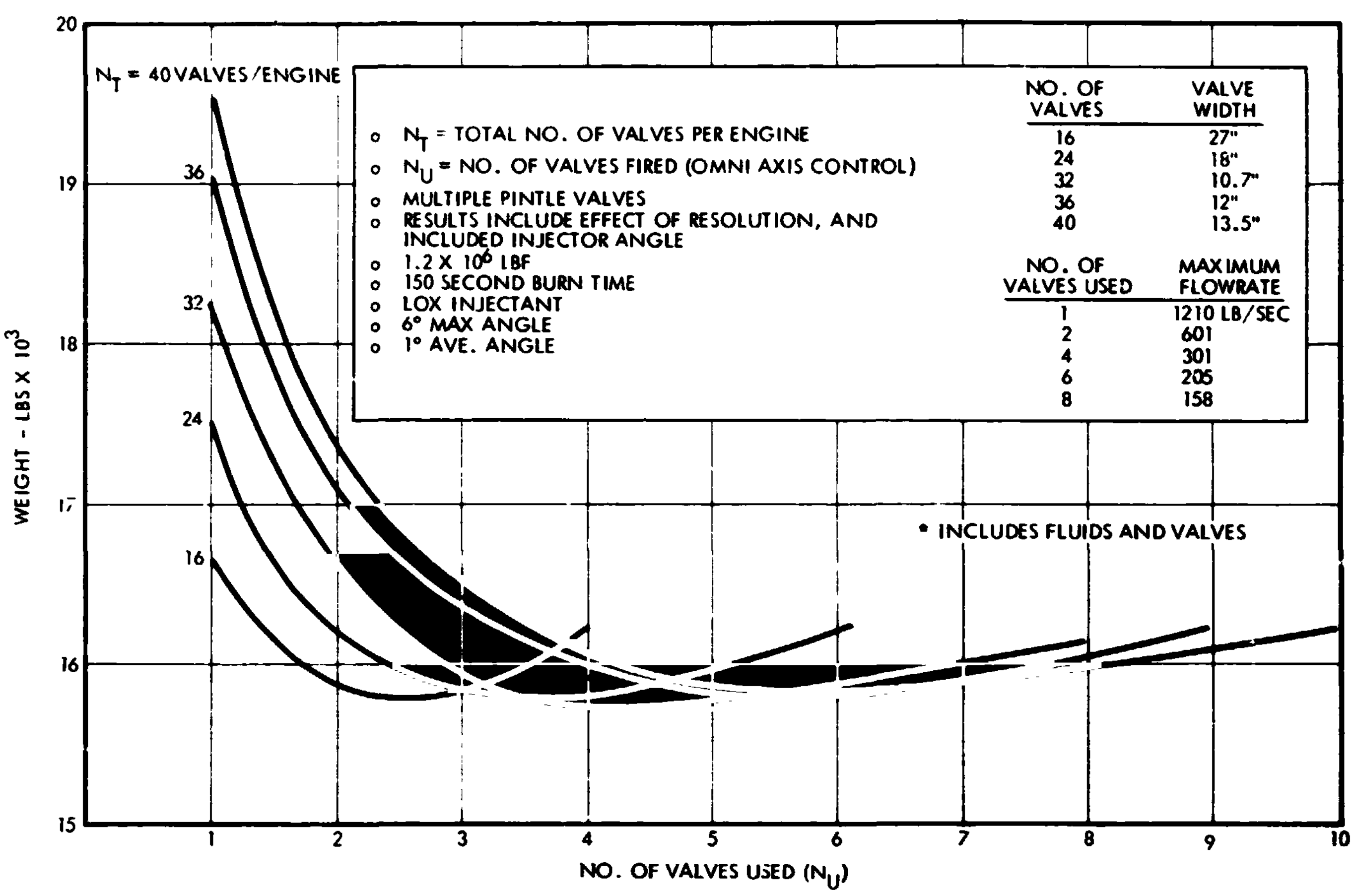


Figure 2.2.1-5. LITVC Weight vs. Number of Valves

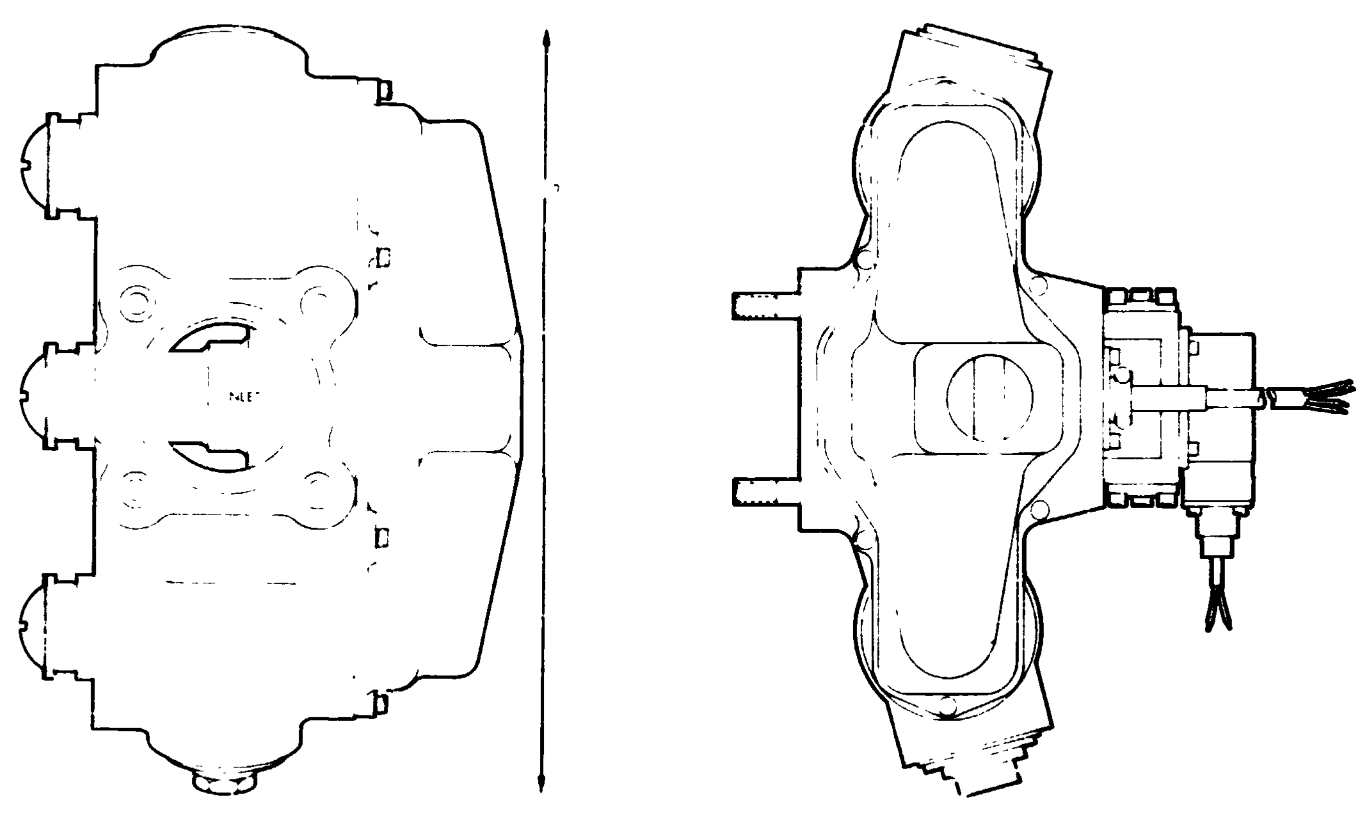


Figure 2.2.1-6. LITVC Servo Injector Valve

2. A two stage, solenoid piloted fuel igniter valve.
3. A two stage, solenoid piloted throttle actuator for injector controlled throttling.
4. A two stage, solenoid piloted throt[illegible] actuator for injector trim mixture ratio control.
5. Pitch and yaw thrust vector control actuators with high pressure RP-1 gimbal actuators.
6. Separate engine control assemblies (ECA's) for each engine plus a stage control assembly (SCA) for vehicle electrical interfacing.
7. Pressure, temperature and accelerometer instrumentation for ground checkout, flight telemetry data, engine startup/shutdown sequenc- and abort override functions.

The following sections describe the control logic and operation of each of these functions.

Electrical Requirements

The primary power source for position control of the major mechanical components will be either high pressure (3000 psia) or line pressure (380 psia) RP-1 and the electrical requirements for the pressure fed engine consist of pilot valve power, control signal circuitry and instrumentation data trans[illegible]ission. Figure 2.3 -1 shows the basic electrical layout indicating the major vehicle and ground support modules. The stage control assembly (SCA) provides the vehicle interface for all seven engines. This requires 154 leads on the vehicle side of which most (140) are required to handle the valve(s) position and engine pressure, temperature and accelerometer data. There are 34 leads between the SCA and each ECA. Between the ECA and the electrical components located on the engine 130 leads are required. The use of redundant actuator pilot valves increases this to 140. An alternate approach to be considered is a commutated digital input which would reduce the number of channels while adding A/D and D/A connectors. Each ECA also includes a ground interface connector for engine acceptance and integration test purposes as well as preflight checkout. The electrical continuity of each ECA circuit is also checked in this manner.

A 28 vdc power supply is required and voltage regulation for transducers will be accommodated within the ECA. The power requirements for each [illegible] listed below. The maximum peak power requirement for the base- [illegible] 243 watts. If LITVC is used the peak total becomes 274

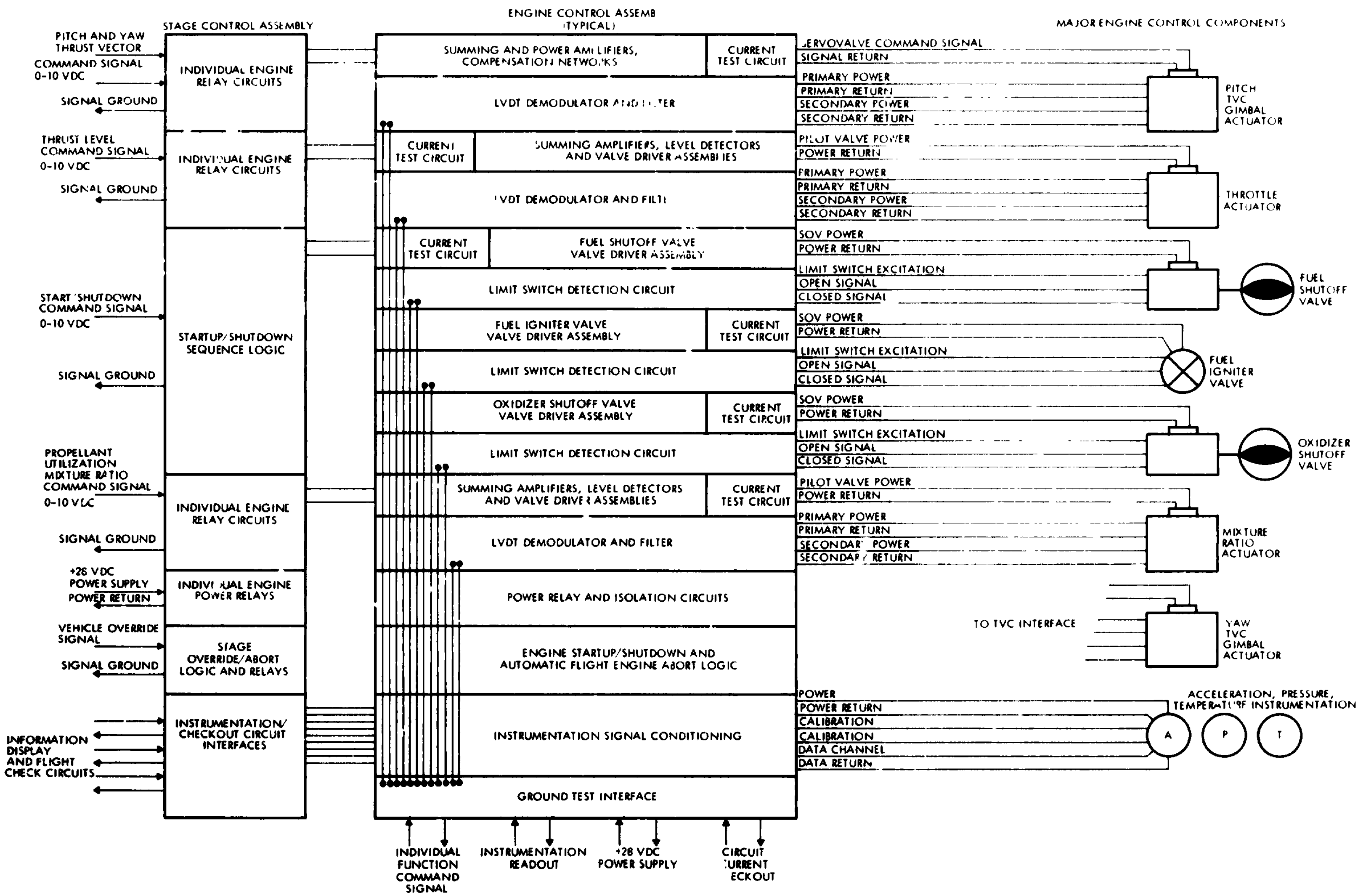


Figure 2.3-1. Electrical System Schematic

based on the use of 32 servoinjector valves controlling 12 at a time (6 on and 6 off).

Item	Peak Power
Fuel shutoff pilot valve	60 watts
Oxidizer shutoff pilot valve	60 watts
Fuel igniter pilot valve	28 watts
TVC gimbal actuators (2)	5 watts
LITVC servoinjector valves* (32)	36 watts
Throttle actuator	30 watts
Propellant utilization actuator	30 watts
Instrumentation	20 watts
ECA	10 watts
Maximum Peak Power	243/274*

*Alternate LITVC Approach

2.4 DYNAMIC STABILITY

The PFE was critically examined for potential high frequency and low feed system oriented frequency problems. It was found to be a quite stable system.

2.4.1 High Frequency Stability Approach

The TRW coaxial injector concept has been test fired in a variety of programs in engines ranging in size from 25 lbf to 250,000 lbf. Stability evaluations have been conducted in many of the engine sizes. These evaluations have included nondirectional bombing as well as pulse gun evaluations. Overpressures have been carried to 150 percent of P_c and in all cases, the recovery times have been on the order of 10 to 15 ms. Typical recovery results are shown in Figure 2.4.1-1 for the LMDE and 250K engines operating with storables and a more recent 50K engine firing with LO_2/RP-1 (250 psia, 2.4:1 MR). Also shown is a result for the 250K throttled 5:1. These results strongly support the TRW analytical studies and assertions that the concept will be dynamically stable at the PFE size for the Space Shuttle Booster application. In summary, in over 20,000 engine and thrust chamber tests and hundreds of thousands of seconds of operation TRW's injectors have never experienced a single case of combustion instability.

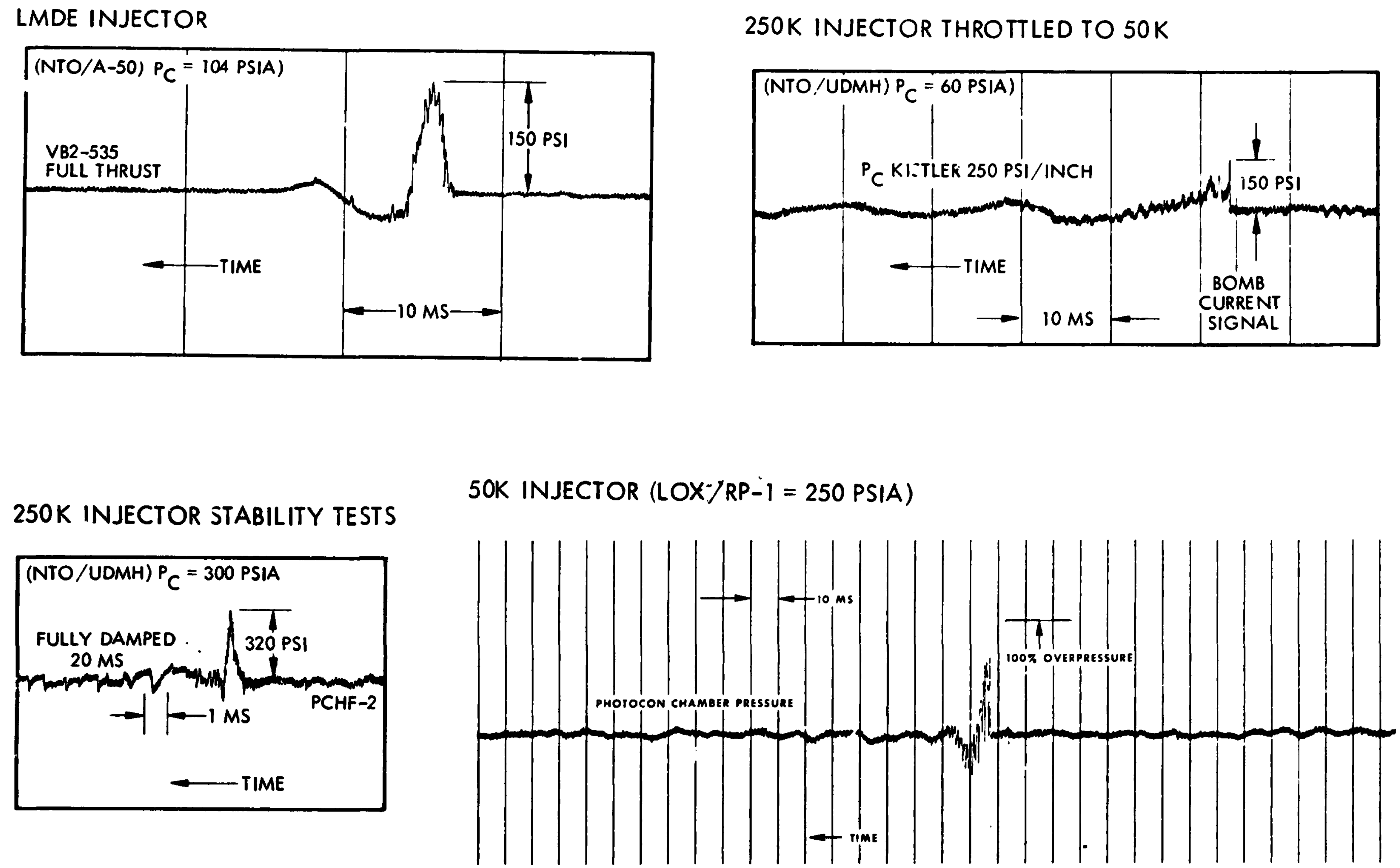


Figure 2.4.1-1. Typical TRW Coaxial Injector Dynamic Stability Evaluations

To substantiate the reliability of the previously observed behavior a small subcontract was issued to Dynamic Science to conduct analytical investigations of the coaxial injector's expected stability characteristics.

The analysis was performed using two computer programs developed by Dynamic Science. The first program calculates steady state performance parameters as functions of injector design variables. These parameters are then input to the nonlinear instability program developed from the Priem-Gueitert model, as functions of axial and radial coordinates and perturbed analytically to determine the extent and sensitivity of the expected sensitive regions of the engine.

Results of the steady-state analysis were examined to determine regions of potential instability. These regions should exhibit low lag ($|\Delta V| < .02$), high fuel vaporization rate ($\mathcal{L} \rightarrow 1$) and should be located far from the chamber axis ($r \rightarrow r_c$). In the TRW PFE engine the only region found that could possibly show instability was near the atomization plane where the gas phase acceleration overtakes the droplet injection velocity. This is also the most sensitive region in a conventional combuster. In the TRW PFE 1200K engine, however, this region occurs only at low radius ($r \doteq 18"$). Calculations using the combustion instability analysis showed this region to be absolutely stable.

Since the fuel vaporization rate is increasing rapidly near the atomization plane due to droplet heat-up, it is difficult to accurately assess the true value of the burning rate parameter, ℓ , in this region. Consequently some doubt is cast on the results of the stability calculations obtained for a conventional injector design. The least stable region was found to be at $r = r_c$ just downstream of the atomization plane. Calculations using the combustion instability program showed this region to be <u>unstable</u>. The neutral stability point for this region was established and a plot of pressure average vs characteristic time is presented in Figure 2.4.1-2 for an initial disturbance just exceeding the stability limit. The characteristic time required for a disturbance traveling at sonic speed to travel once around the annular circumference is 2π. It is evident that after characteristic time = 2π the initial pressure disturbance (assumed to be sinusoidal with $\Delta P \approx \pm 015$) has been amplified.

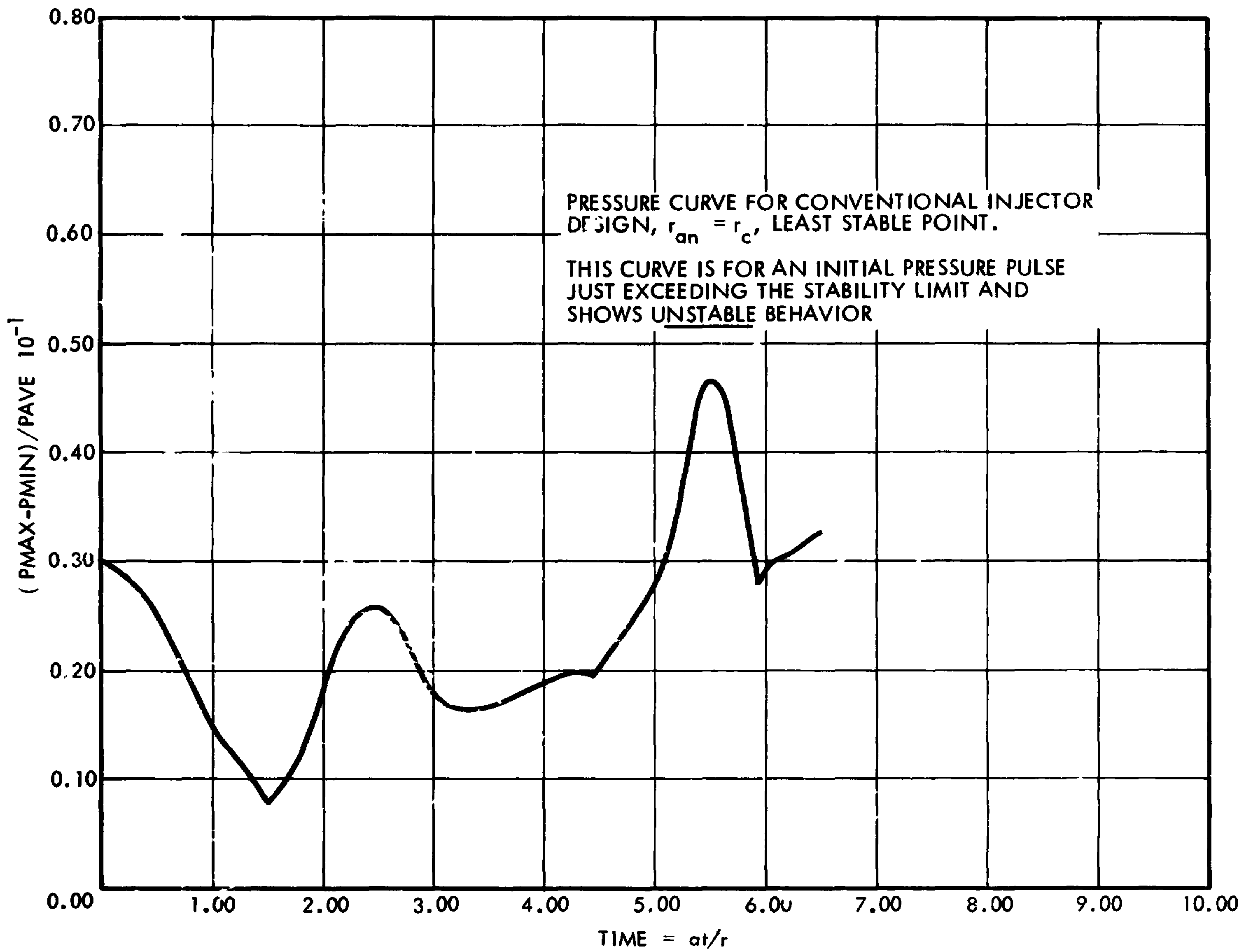


Figure 2.4.1-2. Conventional Injector Response to Perturbation at its Stability Limit

Next, calculations were made for the most sensitive region found for the TRW engine. Two such calculations are presented in Figure 2.4.1-3. The upper curve shows the behavior of the least stable point found with $|\Delta V| < .01$ and the lower curve shows the behavior of a point somewhat downstream with a higher burning rate parameter but with $\Delta V = .02$. Both points were subjected to an identical initial pressure disturbance. It can be seen that the TRW case is very stable since the pressure disturbance is rapidly damped, as seen experimentally.

2.4.2 PFE Low Frequency Dynamic Characteristics

A detailed evaluation of the PFE low frequency dynamic characteristics has shown that the system is inherently stable and will not sustain a low frequency chugging mode. The 5-7 millisecond combustion delay characteristic of the coaxial pintle injector results in a critically damped system for the anticipated booster configuration. Figure 2.4.2-1 shows that no resonant condition exists where a chamber pressure disturbance can be amplified. The oxidizer and fuel injector drops provide a high stability margin. Thus, the engine can be throttled by tank pressure blowdown to at least the 70% point. The use of injector throttling with blowdown of tank pressure would allow the throttle point to be lowered at least 40%. Similarly, the engine will not amplify cyclic disturbances in tank bottom pressure as shown in Figure 2.4.2-2. Figure 2.4.2-3 summarizes the low frequency response characteristics.

Additional studies have shown that either LITVC or gimbal TVC can be incorporated with achievable slew rates of at least 20 deg/sec with both fluid and mechanical stability. The engine will also meet the 3 $\pm$ 0.05 second (90% chamber pressures) and 700,000 lbs/sec (maximum thrust buildup rate) startup requirements with good margins. No problems are therefore anticipated in meeting any of the currently specified control and response requirements of the PFE.

2.4.3 POGO Evaluation Summary

The results of the propulsion system dynamic analyses have been used to evaluate the possibility of POGO-type instability. The three most probable modes (Figure 2.4.3-1) were evaluated with the results showing that a low probability of occurrence can be achieved through the use of good design techniques.

C.2

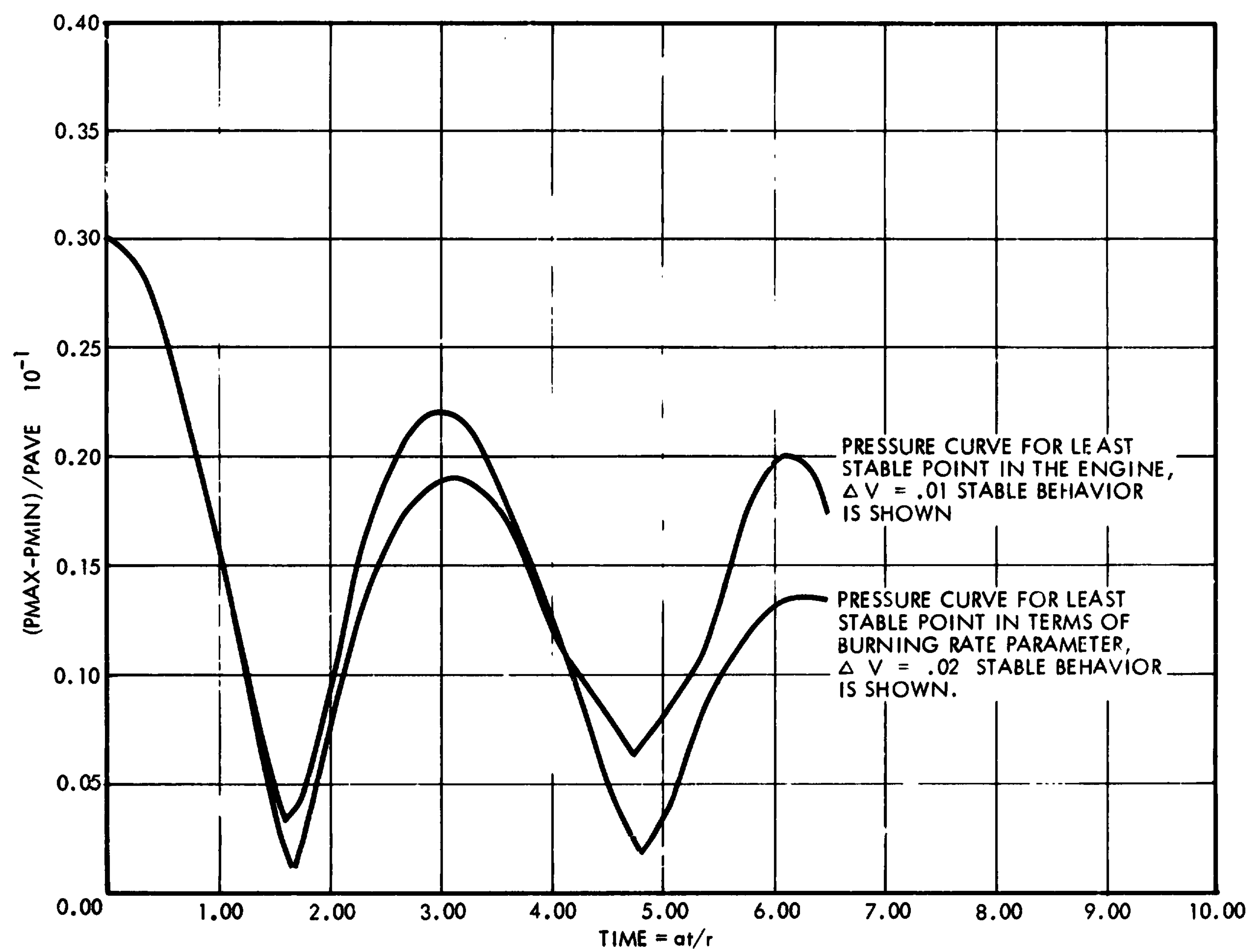


Figure 2.4.1-3. TRW PFE Response to Disturbance, Indicating Strong Drive to Stability

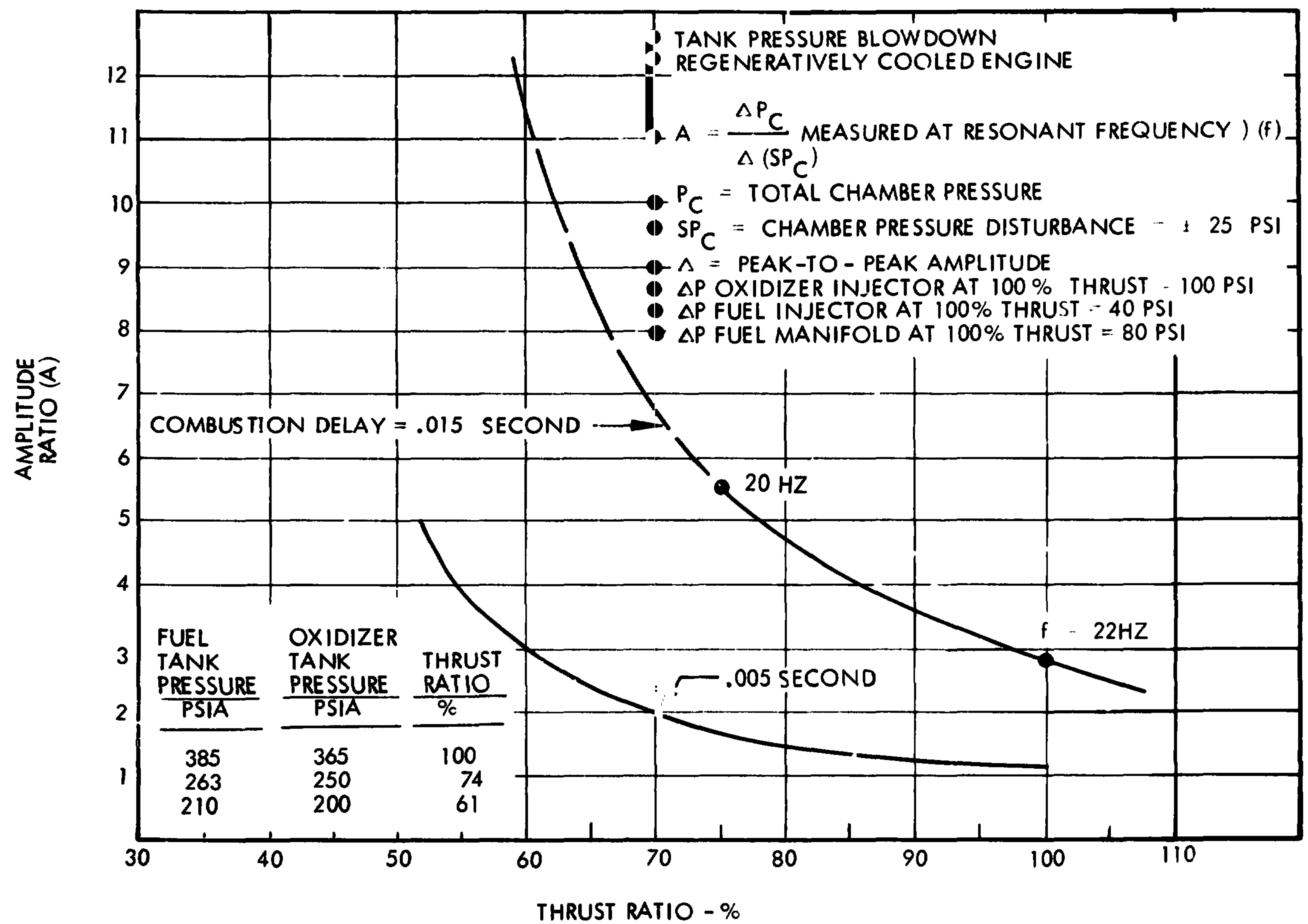


Figure 2.4.2-1. Low Frequency Amplitude Ratio vs. Thrust Ratio

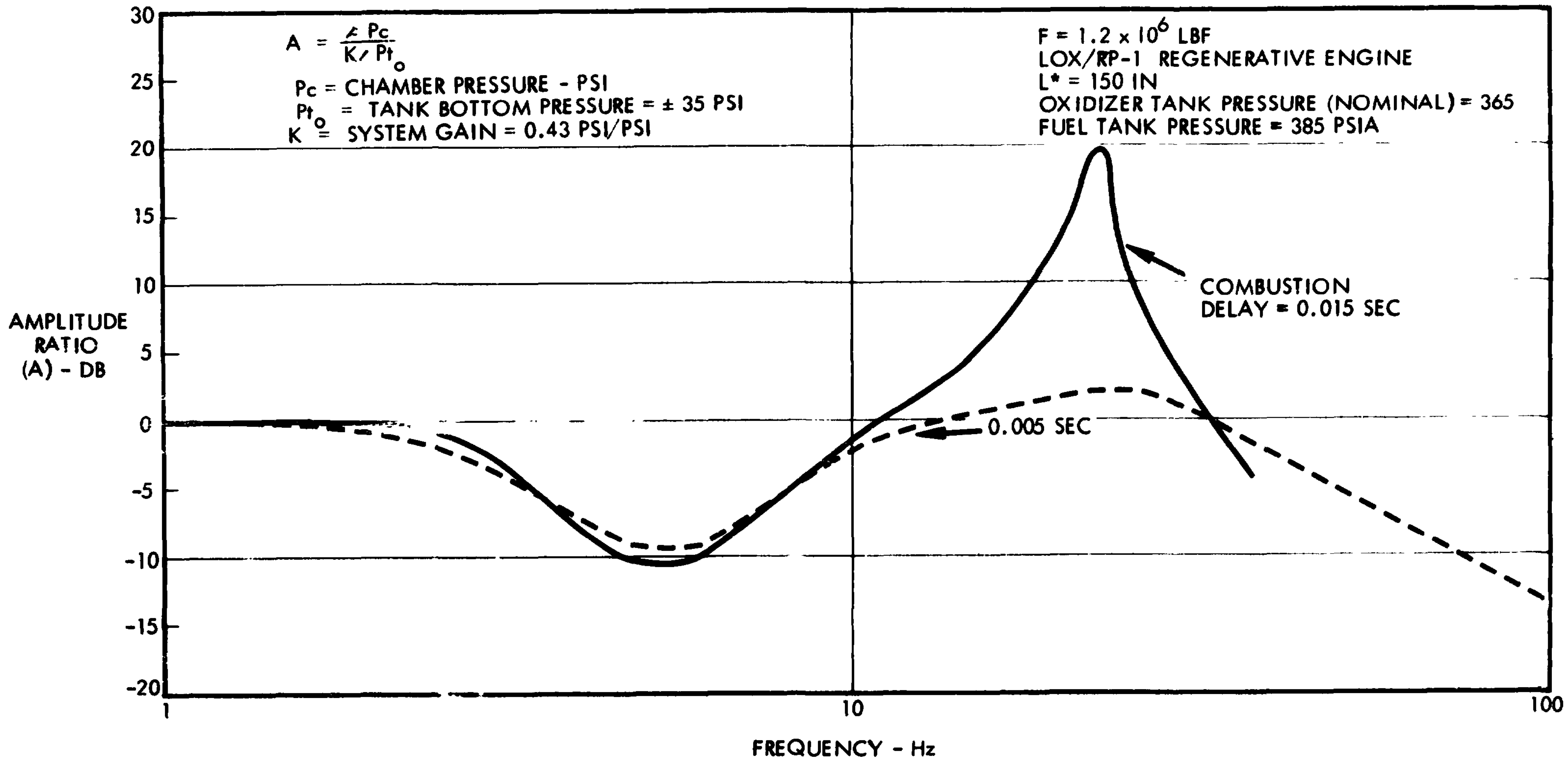
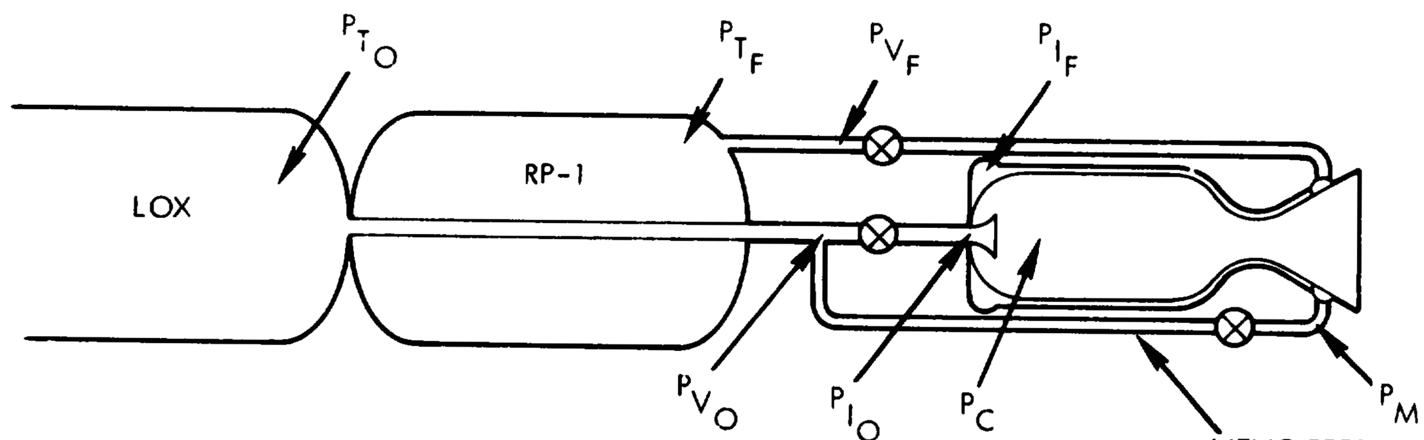
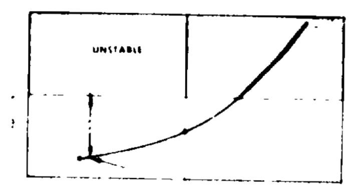


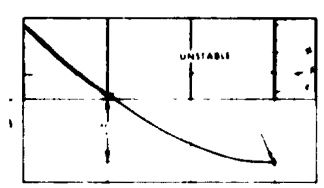
Figure 2.4.2-2. Effect of Tank Bottom Pressure Disturbances



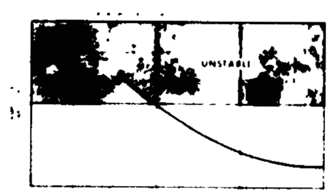
1.2 X 10^6 LBF REGENERATIVE ENGINE MODEL



COMBUSTION DELAY OF .005 - .007 SECOND PLUS 150" L* CHAMBER PROVIDES CRITICALLY DAMPED SYSTEM PREVENTING LOW FREQUENCY INSTABILITY

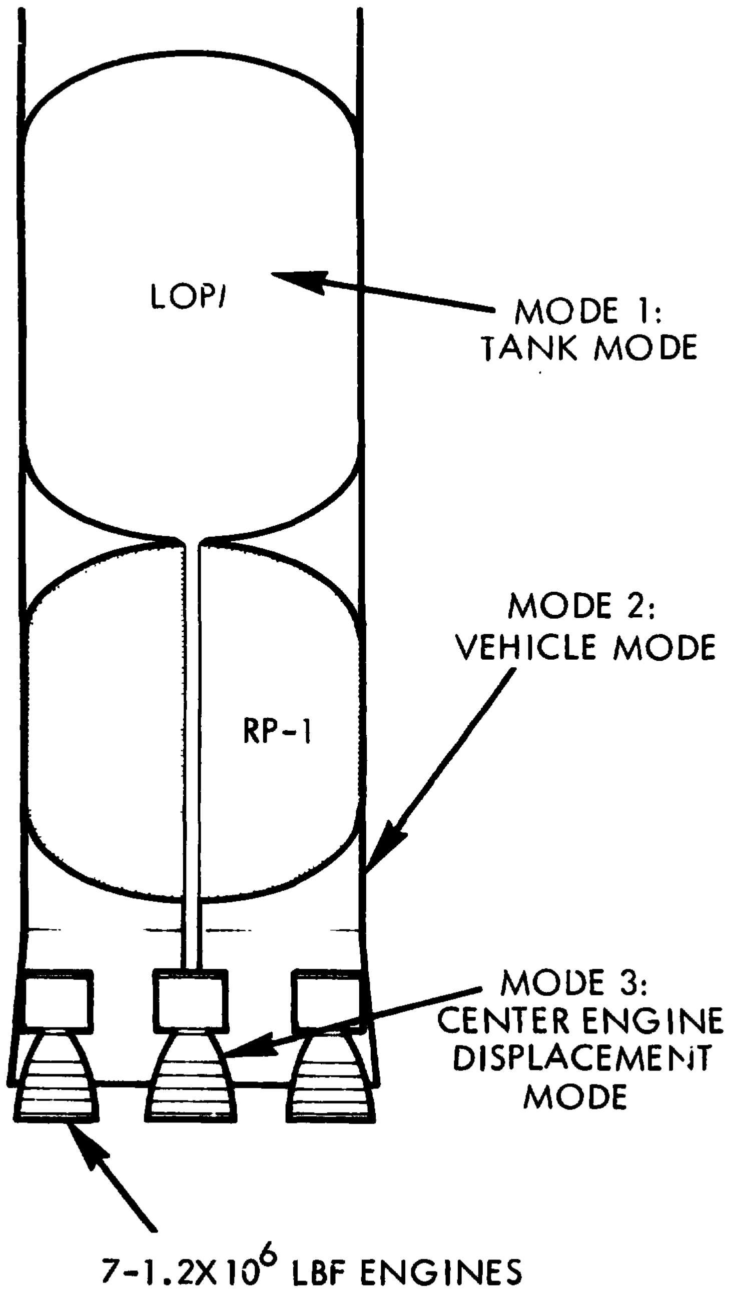


100 PSID LOX AND 40 PSID RP-1 INJECTOR PRESSURE DROPS PROVIDE SUBSTANTIAL STABILITY MARGIN



CURRENT DESIGN ALLOWS TANK PRESSURE THROTTLING TO 60%. INJECTOR THROTTLING (FULL TANK PRESSURE) TO AT LEAST 25% CAN BE PROVIDED WITH STABLE OPERATION.

Figure 2.4.2-3. PFE Low Frequency Characteristics Summary



MODE 1	NATURAL FREQUENCY:	1.05 HZ - BEGINNING OF FLIGHT 0.75 HZ - END OF FLIGHT
	LOOP GAIN:	0.17 PSI/PSI OF CHAMBER PRESSURE DISTURBANCE
	CONCLUSION:	NO PROPULSION SYSTEM COUPLING DUE TO HIGH PRESSURE TANK DESIGN
MODE 2	NATURAL FREQUENCY:	5.4 HZ - BEGINNING OF FLIGHT 24.0 HZ - END OF FLIGHT
	LOOP GAIN:	0.0013 PSI/PSI OF CHAMBER PRESSURE DISTURBANCE
	CONCLUSION:	MINIMUM POSSIBILITY OF COUPLING NEAR END OF FLIGHT - ELIMINATED BY SLIGHT REDUCTION IN PROPULSION SYSTEM FREQUENCY (ADDED RESISTANCE, CAPACITANCE OR INERTANCE)
MODE 3	NATURAL FREQUENCY:	10.8 HZ
	LOOP GAIN:	0.016 LBF/LBF OF THRUST DISTURBANCE
	CONCLUSION:	POSSIBILITY OF PROPULSION SYSTEM COUPLING ELIMINATED BY CORRECT STRUCTURAL AND FEED SYSTEM GEOMETRY DESIGN (LATERAL LOX FEED).

Figure 2.4.3-1. POGO Evaluation Summary

One expressed concern with the PFE has been the higher sensitivity of chamber pressure to tank pressure compared with a high chamber pressure engine. However, the high pressure tank design more than compensates for this and as a result there exists a high stability margin. Thus, the probability of a tank mode POGO problem is extremely low with the PFE.

A second possibility is a vehicle mode instability in which the stage is excited with respect to the propellant feed system was identified near the end of flight only if the combustion delay time is markedly higher than the anticipated 5-7 milliseconds. This occurs only if the propulsion system and structural resonant frequencies occur at about the same frequency, i.e., 20-25 CPS. Even if this were identified as a problem it would be easy to reduce the propulsion system frequency by 1-5 CPS and therby eliminate such a possibility. Figure 2.4.3-2 shows the relative vehicle mode stability of the system as a function of combustion time. Minimal addition of resistance, capacitance or inertance would provide the above noted propulsion system frequency shift.

The possibility of a center engine coupling mode was also noted at about 11 CPS if a straight down LOX feed line to the engine was incorporated. A straight forward approach designs the feed line geometry such that the relative engine/propellant displacement is reduced. A substantial gain margin can be achieved as shown in Figure 2.4.3-3 by supplying the center engine through a lateral line (or lines) from the outboard engines feed system.

2.5 SPECIFIC PERFORMANCE SUMMARY

PFE performance was estimated for the baseline regeneratively cooled LOX/RP-1 PFE as follows:

Theoretical Performance (S.L)		250.0 SEC
(Vacuum)		303.7 SEC
Combustion Efficiency	95.0%	
Kinetic Efficiency	99.8%	
Divergence Efficiency	97.7%	
Viscous Drag	99.6%	
Cooling	100.0%	
Delivered Performance (S.L)		230.7 SEC
(Vacuum)		280.2 SEC

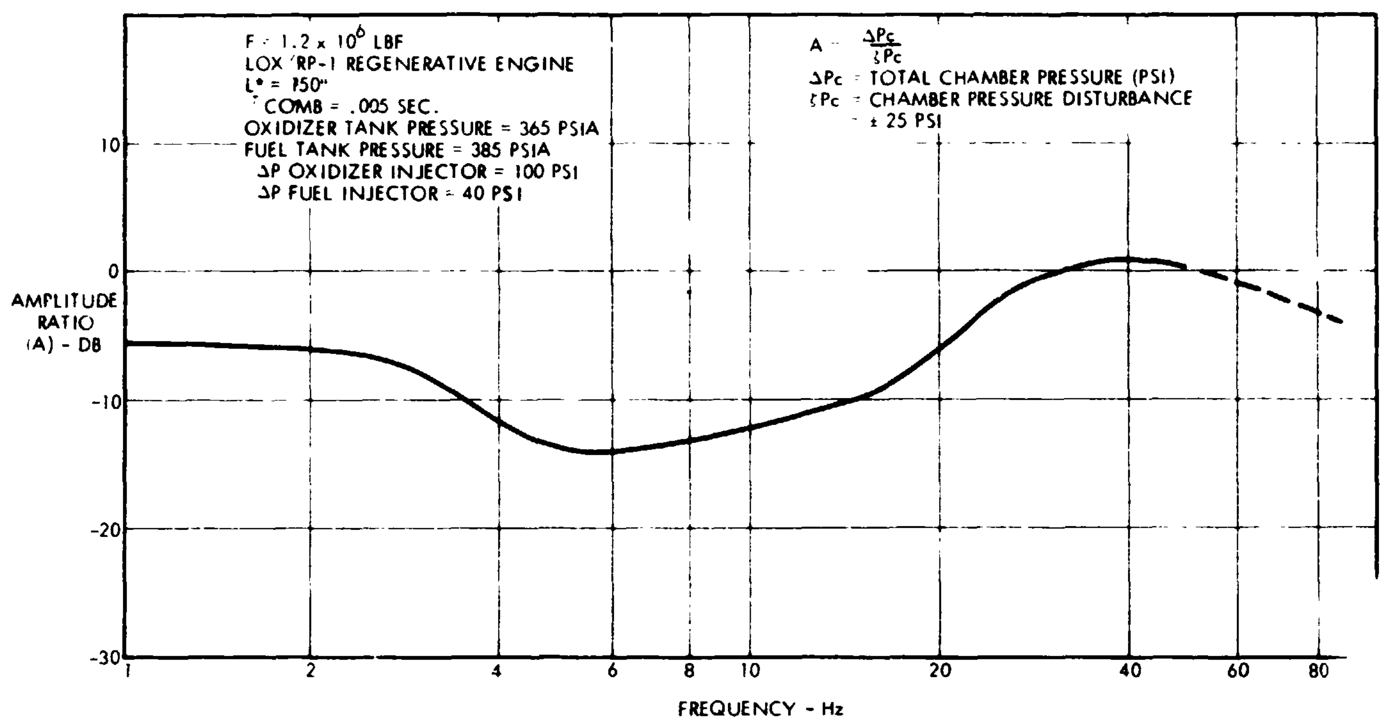


Figure 2.4.2-1. Low Frequency Amplitude Ratio for Chamber Pressure Disturbances

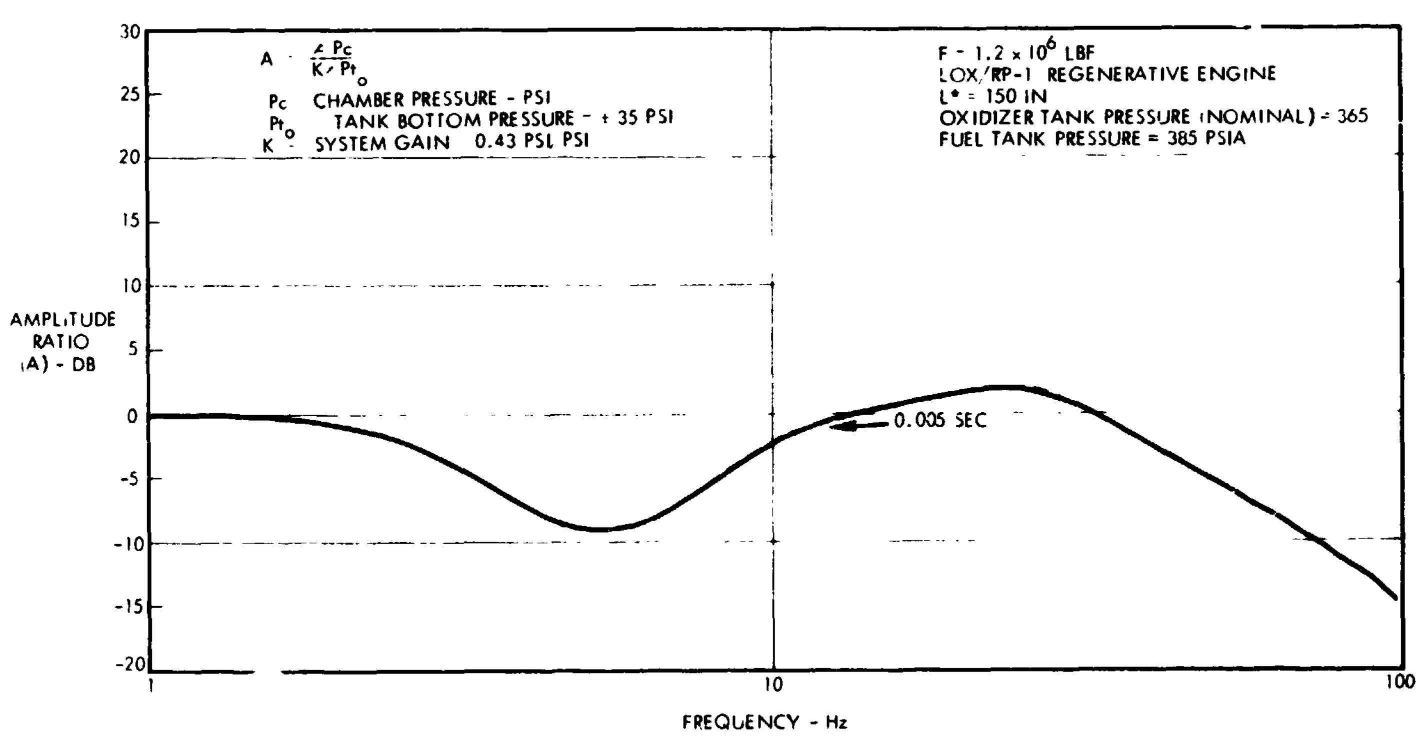


Figure 2.4.2-2. Amplitude Ratio for Tank Bottom Pressure Disturbances

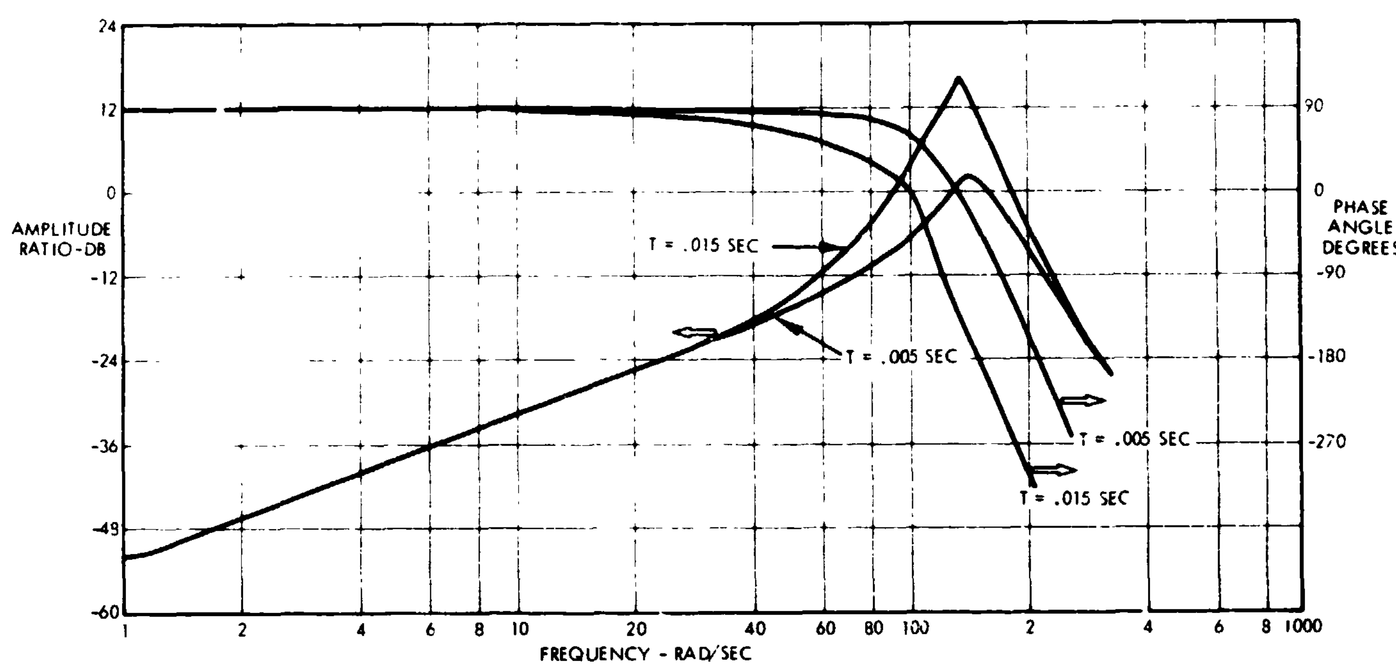


Figure 2.4.3-1. Vehicle Mode

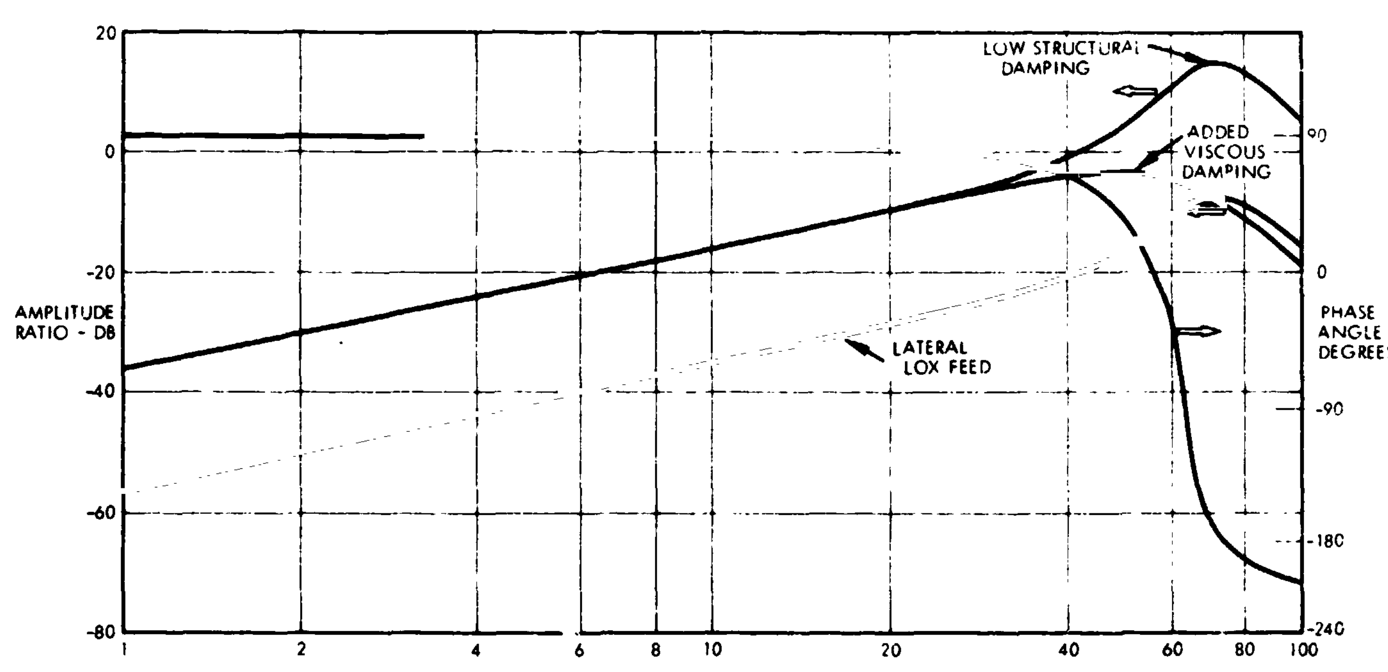


Figure 2.4.3-2. Center Engine Displacement Mode

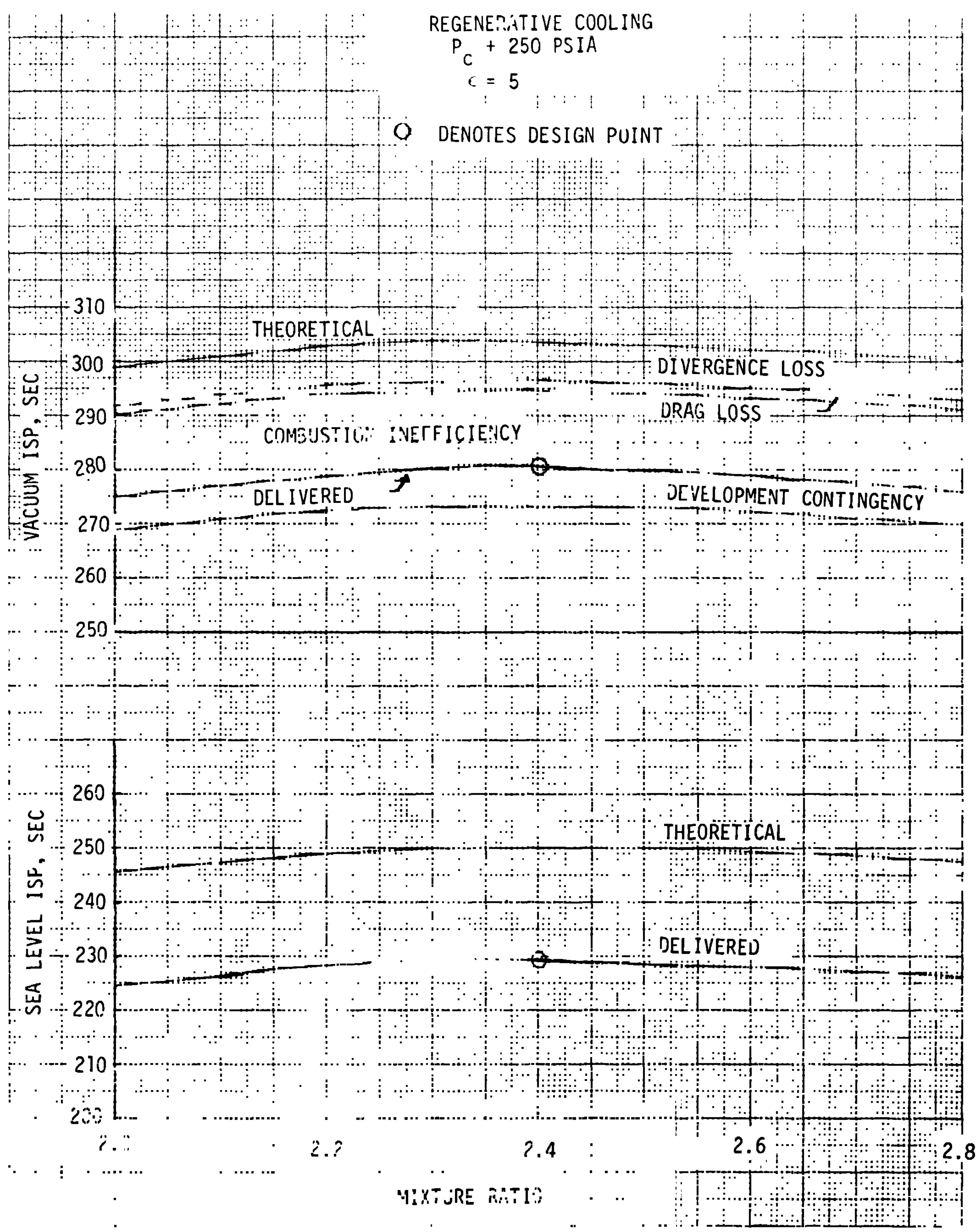


Figure 2.5-1. Specific Impulse of LOX/RP-1 vs. Mixture Ratio

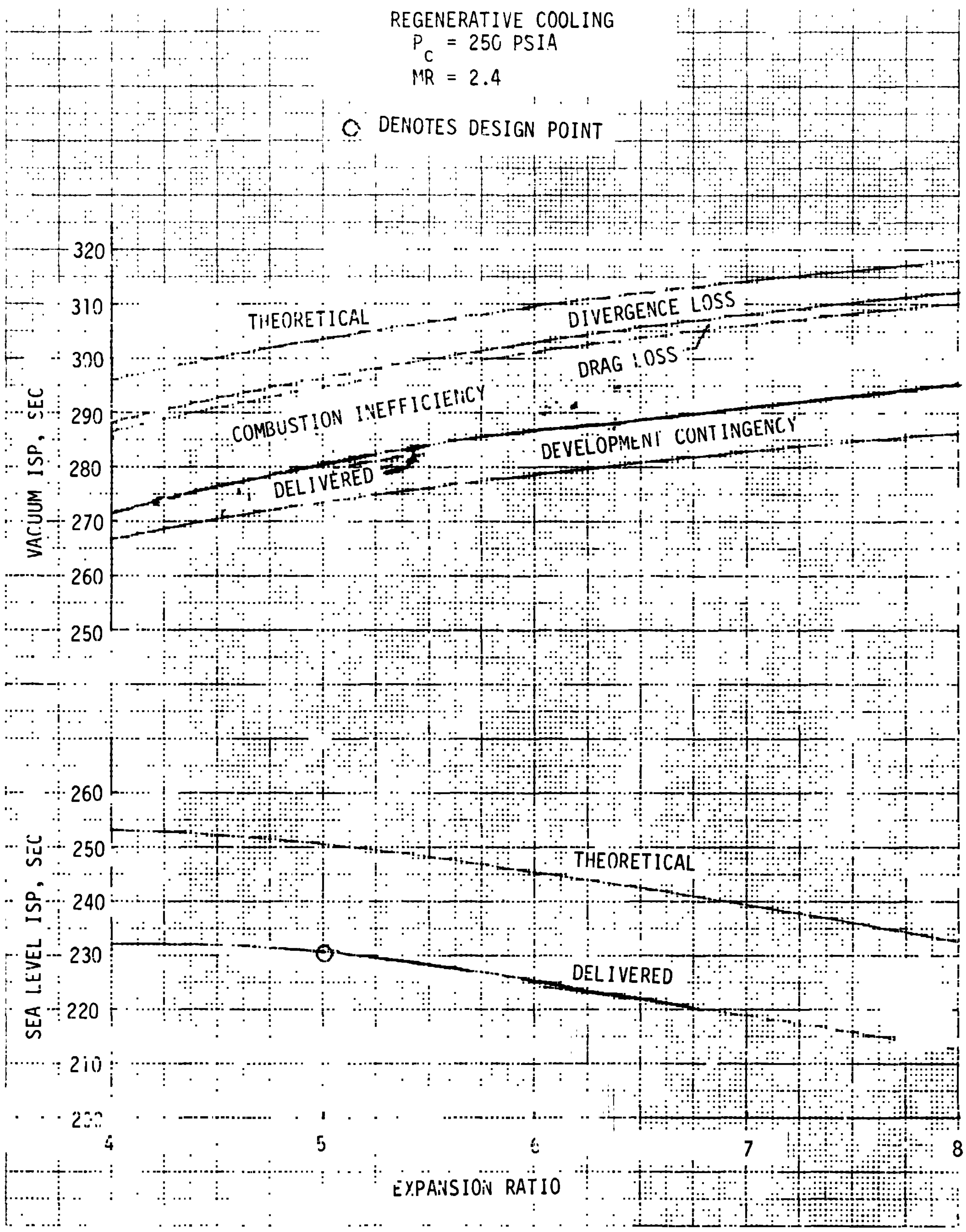


Figure 2.5-2. Specific Impulse of LOX/RP-1 vs. Nozzle Area Ratio

The above represent nominal delivered performance values at a mixture ratio of 2.4:1, area ratio of 5:1, and chamber pressure 250 psia. Graphical portrayal of the theoretical performance, deviation from theoretical and delivered performance (for both S.L and Vacuum) are presented in Figures 2.5-1 and 2.5-2 as functions of mixture ratio and expansion ratio. Also shown in the curves are the difference between the nominal delivered performance and 90 percent of the theoretical performance. This difference can be considered a development contingency.

3. PFE PROGRAM

The pressure fed engine program is depicted in Figure 3-1 with its major activities including: (1) supporting technology programs designed to evaluate key critical questions such as scaling, stability, and performance, (2) engine system design and integration, (3) production and deliveries, (4) flight support. The PFE program primary milestones are ATP (1972) assumed to be July 1, 1972, CDR (January 1975), PFC (July 1976) and FFC (January 1977). This is compatible with a FMOF in March 1978.

The supporting technology efforts are key to the preliminary design and provide confidence in the design approaches and critical design release dates. The recommended supporting technology program efforts include 50K, 250K and 1200K hot firings in boiler plate hardware. These firings are relatively inexpensive and can be accomplished within the first 9-12 months of the program. As an example, a 1200K boiler plate firing program by TRW Systems can be accomplished for ~ $1M. The results would include performance, stability evaluations, heat flux, feed system coupling reactions, and ignition data. The basic design data for the injector would then be available to the PDR.

The development program is planned with a first all up engine firing 19 months into the schedule from ATP. A review of the manufacturing requirements, vendor support requirements, and facility modifications indicates a sufficient margin of calendar time to meet the schedule.

The EAFB facility is selected as the primary development facility. The program requires the facility preparation to be initiated at ATP. The component firing positions are required for the supporting technology efforts as well as the initial chamber, ignition, and injector evaluation efforts.

The engine design approach suggests that a life of 50 missions is within the state-of-the-art today. Therefore the refurbishment operations can be reduced to maintenance functions for the most part with only occasional total engine over[illegible] necessary. This minimizes the cost of the support function [illegible] ries through the end of the program (1989).

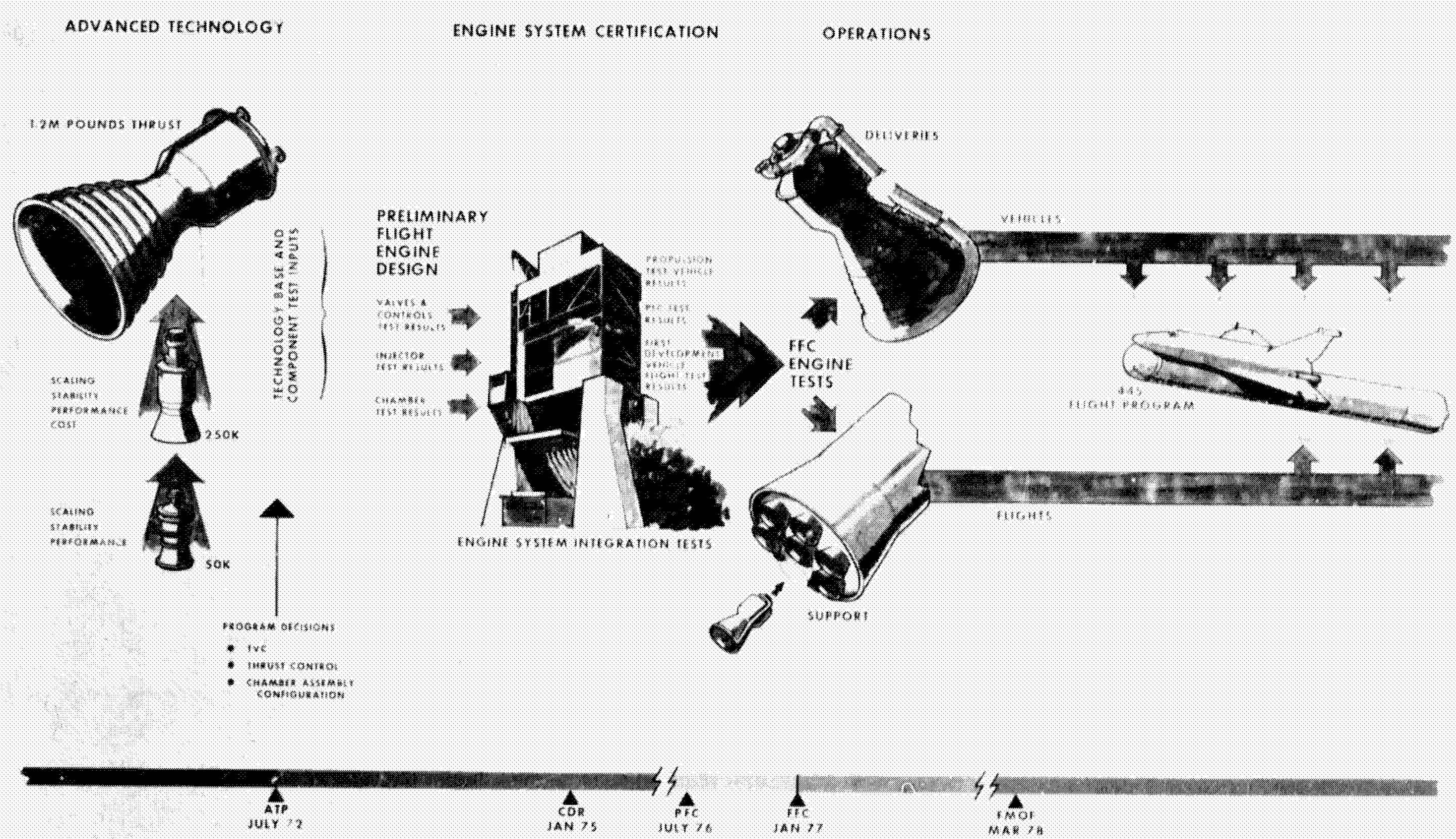


Figure 3-1. Reusable Pressure Fed Booster Engine Program

3.1 PHASE C/D OVERVIEW

The program schedule (Figure 3.1-1) has been prepared on three bases: (1) a baseline program with 3/1/78 FMOF, (2) a maximum success program with a mid 1977 FMOF, and (3) a most probable program with a 1/1/79 FMOF. The nominal development program is a 54 month program through FFC. The program provides for an extensive component development effort which allows a first all up engine firing 18 months after ATP.

The component effort runs injector and ignition development in parallel with thrust chamber development. Similarly the valving, actuator and other control functions are being developed in the same period of time.

Activation of the EAFB 2A facility to receive the first development hardware 4 to 5 months into the program must occur at ATP. Similarly the refurbishment of the 1B stand to receive the first thrust chamber for extended duration testing approximately 9 months later must begin at ATP.

The development engine program includes mission duty cycle runs with simulated reentry heating, splashdown quenching and water impact loading, sea water immersion, refurbishment cycles and refiring tests.

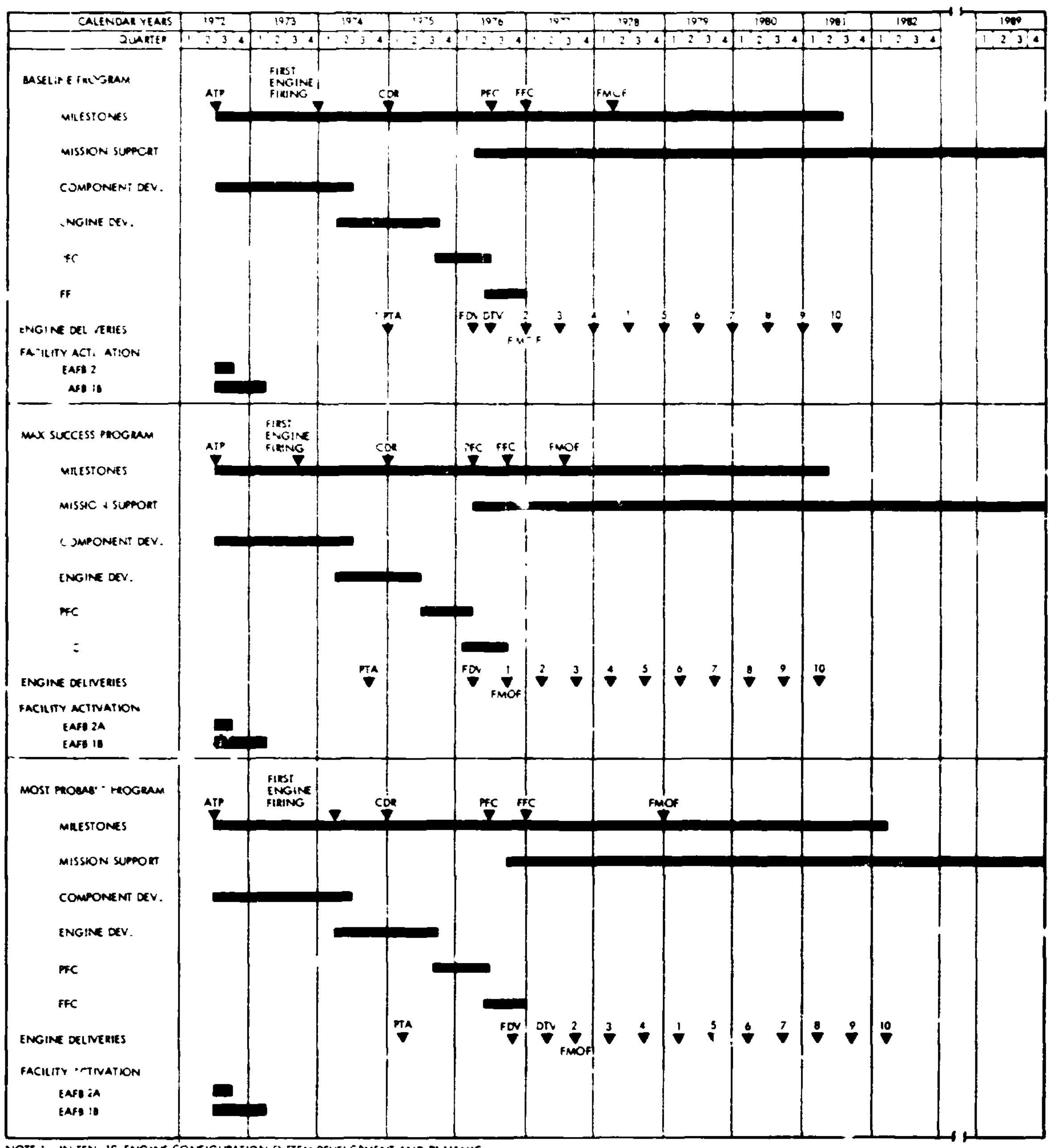
The flight engine deliveries are spaced at even increments beyond FMOF.

The maximum success program enables the FMOF point to move forward in time approximately 9 months. To accomplish it additional hardware and parallel testing is required, with a minimum of development difficulty to be expected.

The most probable schedule results in a 9 month FMOF schedule slippage.

3.2 REUSABLE PRESSURE FED BOOSTER ENGINE CONFIGURATION DEFINITION APPROACH

The design basis for the reusable pressure fed booster engine configuration definition (Figure 3.2-1) will be initially established by the advance technology testing performed on the 50K, 250K and 1.2M lb workhorse thrust chamber assemblies. The results of this early work will be utilized to design the injector, thrust chamber assembly and valves and controls component test hardware. The results of the component testing will provide the information for the preliminary integration engine



NOTE: IN TEN (10) ENGINE CONFIGURATION SYSTEM DEVELOPMENT AND DYNAMIC VEHICLE ENGINE DELIVERIES ARE FIVE (5) ENGINES

Figure 3.1-1. Pressure Fed Engine Program Schedule

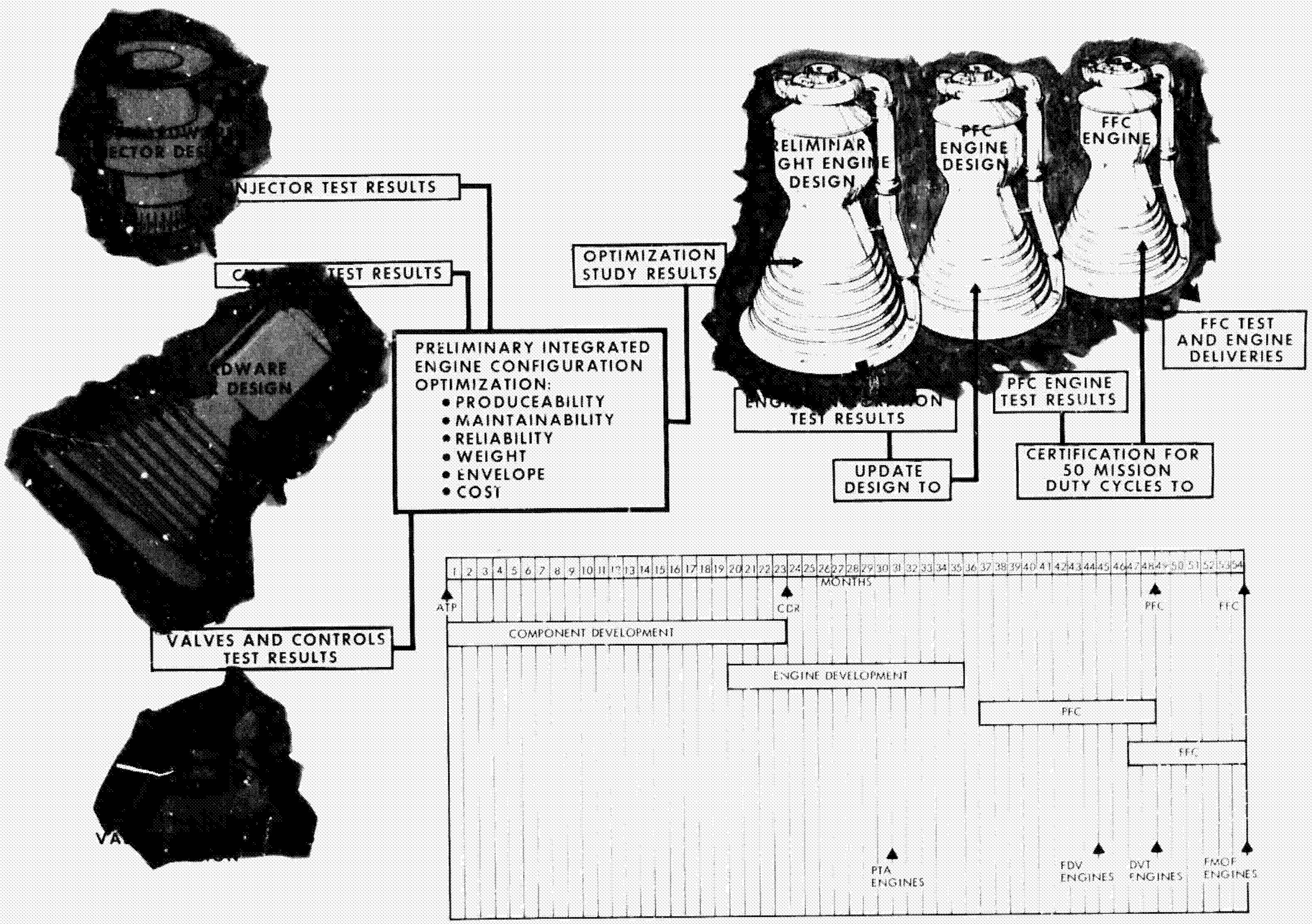


Figure 3.2-1. Reusable Pressure Fed Booster Engine Configuration Definition Approach

configuration optimization. This optimization will include obtaining a design with maximum producibility, minimum maintenance, minimum weight consistent with maximum reliability and minimum cost.

The optimization results will culminate in the preliminary flight engine design which will be subjected to extensive integration tests. The integration test program including engine repeatability, performance, life, limit, off limit, stability and structural integrity will verigy the design approach and with some updating based on these test results provide the preliminary flight certification (PFC) engine design.

The PFC tests will verify the ability of the engine to provide satisfactory operation for 50 reuses. Minor changes, if any, will be made to the design to produce the engine for final flight certification (FFC).

3.3 PROGRAM SCHEDULE TO PRELIMINARY FLIGHT ENGINE FIRING

A critical part of any development program is the achievement of the first all up engine firing as early as possible in the program. An engine design weakness may not appear until this firing. This time for the TRW PFE is projected at 18 to 19 months. The first all up engine may not have all flight configured hardware on it, but it must include all flight functions on it. The approach to meeting this date is illustrated in Figure 3.3-1. The injector and chamber designs come out of the component development efforts and as such are test verified to the extent they will satisfy the initial all up engine requirements. As also shown, the anticipated component delivery date is 17 months after ATP. The firing of this engine is scheduled at 19 months. This first all up engine for firing is the number 8 thrust chamber in the fabrication process. The fabrication times are the indicated vendor time. 2 months are allocated to assembly and stand installation.

3.4 COMPONENT TEST AND CERTIFICATION PROGRAM

The development program time and hardware requirements for the PFE are illustrated in Figure 3.4-1. As planned here a sufficient number of tests and quantity of hardware are utilized to provide high confidence in the development results.

Figure 3.4-2 illustrates the engine certification program. The

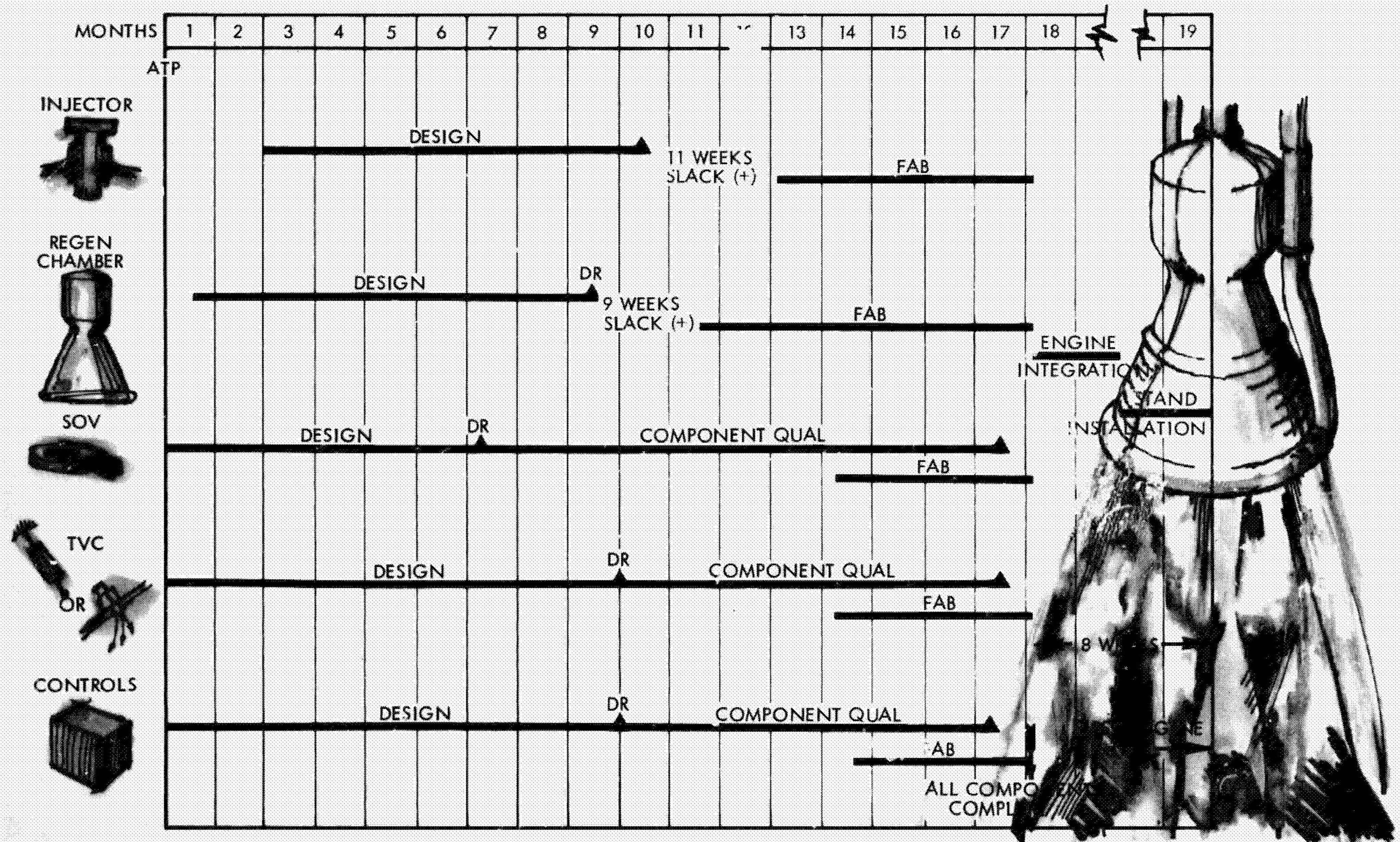
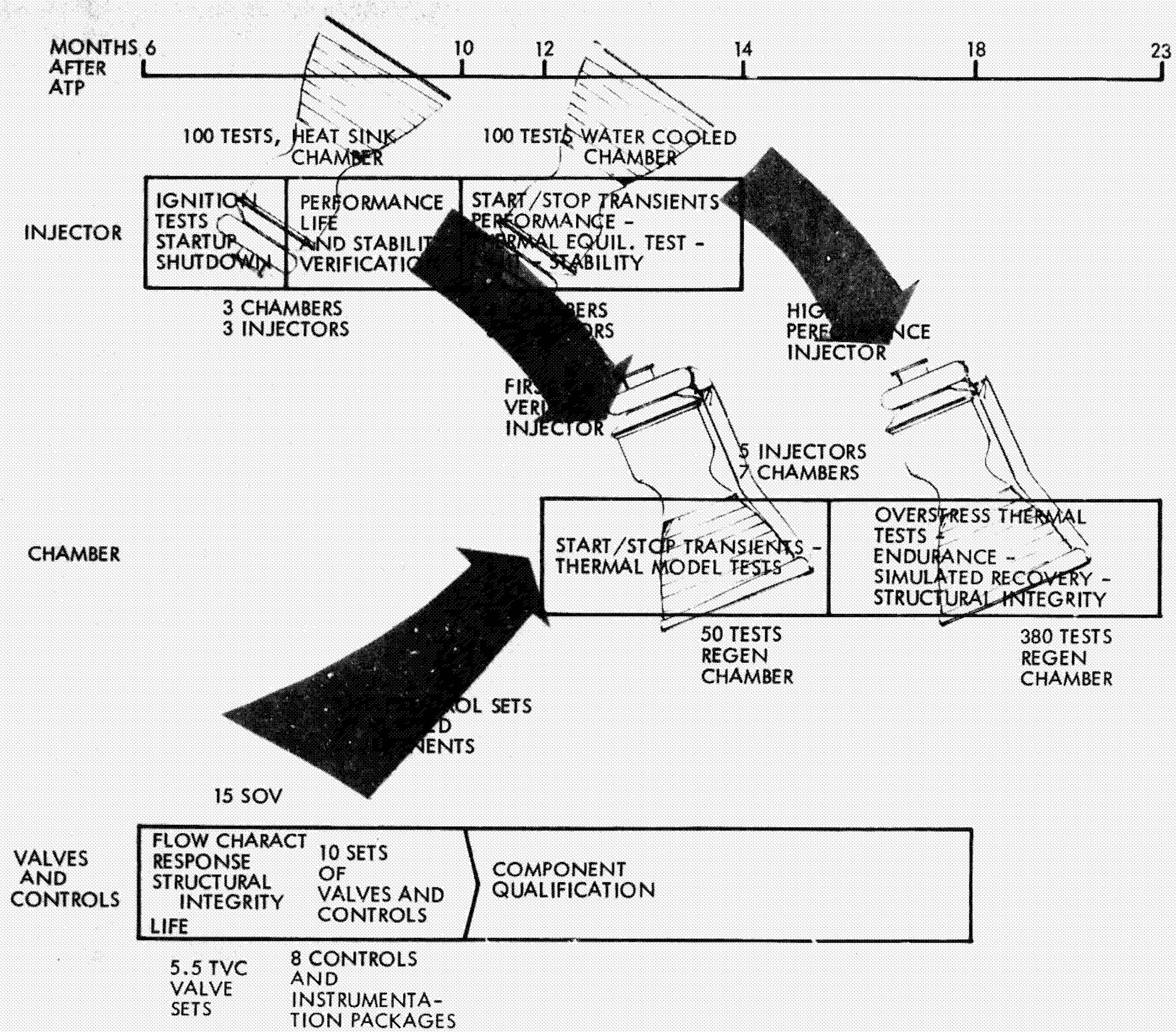


Figure 3.3-1. Program Schedule for Preliminary Flight Engine Firing


MONTHS AFTER ATP
6
10
12
14
18
23
100 TESTS, HEAT SINK CHAMBER
100 TESTS WATER COOLED CHAMBER
INJECTOR
IGNITION TESTS STARTUP SHUTDOWN
PERFORMANCE LIFE AND STABILITY VERIFICATION
START/STOP TRANSIENTS PERFORMANCE - THERMAL EQUIL. TEST - STABILITY
3 CHAMBERS
3 INJECTORS
INJECTOR
5 INJECTORS
7 CHAMBERS
CHAMBER
START/STOP TRANSIENTS - THERMAL MODEL TESTS
OVERSTRESS THERMAL TESTS - ENDURANCE - SIMULATED RECOVERY - STRUCTURAL INTEGRITY
50 TESTS REGEN CHAMBER
380 TESTS REGEN CHAMBER
15 SOV
VALVES AND CONTROLS
FLOW CHARACT RESPONSE STRUCTURAL INTEGRITY LIFE
10 SETS OF VALVES AND CONTROLS
COMPONENT QUALIFICATION
5.5 TVC VALVE SETS
8 CONTROLS AND INSTRUMENTATION PACKAGES

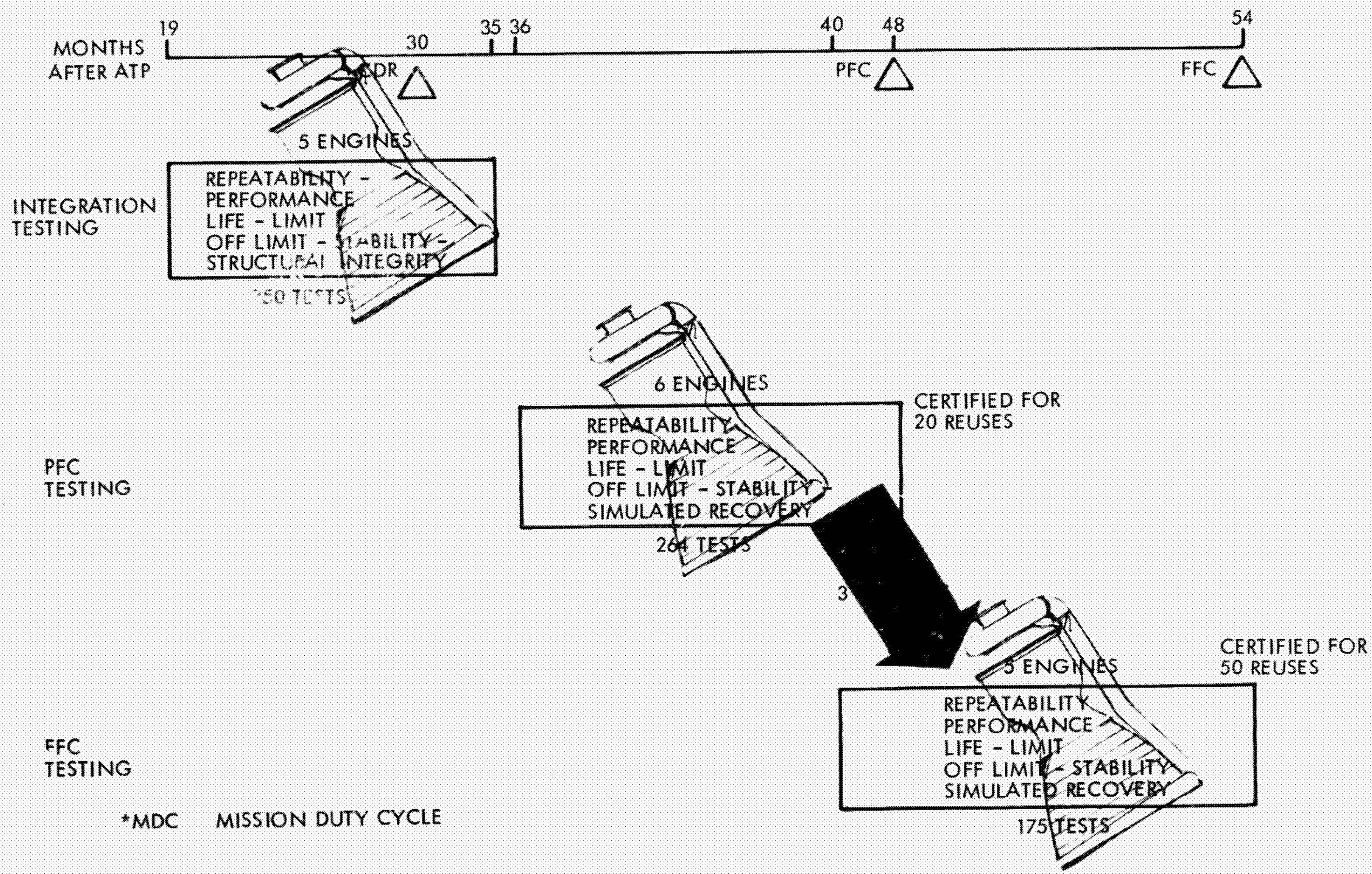


Figure 3.4-2. Reusable Pressure Fed Booster Engine Certification Program

entire effort requires 48 months to PFC and 54 months to FFC.

3.5 TRW REUSABLE PRESSURE FED BOOSTER ENGINE MANUFACTURING FLOW PLAN

The TRW PFE manufacturing program plan (Figure 3.5-1) emphasizes the use of the nation's specialty manufacturing expertise. This approach results in a minimum cost of fabrication and assembly, eliminates the need for development and organization of "one time only" company functions which at the close of the program culminate in large local social upheavals, and allows the PFE program to accelerate rapidly in its initial phases to the point that early proof testing of components can eliminate troublesome development problems.

The major components flow to the major test facility for final engine assembly and checkout. The EAFB test facility would be modified to include this assembly function. This major assembly area would provide necessary engine to reactive test sites at EAFB and the NASA acceptance firing locations. An overhaul and refurbishment center is also established at the launch facility.

The engine delivery rate requirements are compatible with several modes of transportation. Delivery from EAFB to NASA test facilities would be by air utilizing the Super Guppy. Transfer from the NASA facility would be by barge.

A continued cost analysis of the program may indicate that in the production program the major assembly and firing acceptance functions should be combined at the NASA firing site. In this case the above plan is modified only to the extent that the components flow to this site for assembly and checkout.

3.6 PROGRAM COSTS

The projected program costs for the nominal 50 mission TRW PFE are shown in Table 3.6-1 for several engine configurations and schedules. The baseline regenerative, fixed thrust, gimballing engine program is projected at a total cost of \$247.12$\overline{M}$. Adding the throttling, face shut off feature will add about 10% to the program (\$270.65$\overline{M}$). A key feature to the achievement of these costs is in the injector and chamber approach taken by TRW Systems. The injector approach results in an order of magnitude reduction

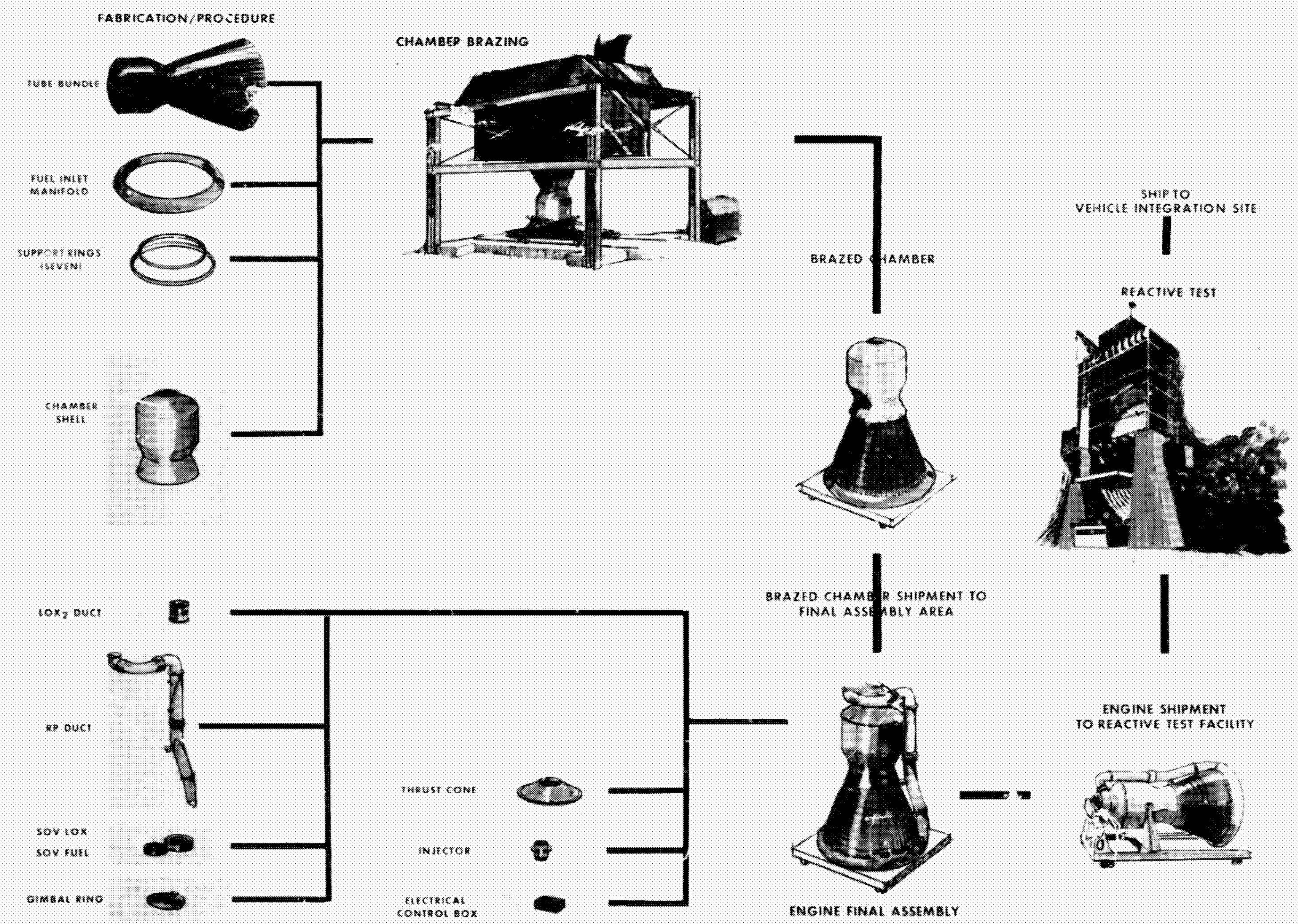


Figure 3.5-1. Reusable Pressure Fed Booster Engine

Table 3.6-1. Space Shuttle Engine Funding Requirements

SCHEDULE	BASELINE					MAXIMUM SUCCESS	MOST PROBABLE
FMOF	3-1-78					8-1-77	1-1-79
THRUST	1200K				600K	1200K	
CONFIGURATION	REGENERATIVE FIXED THRUST GIMBAL	REGENERATIVE THROTTABLE LITVC	REGENERATIVE THROTTABLE GIMBAL	DUCT FIXED THRUST GIMBAL	REGENERATIVE FIXED THRUST GIMBAL	REGENERATIVE FIXED THRUST GIMBAL	REGENERATIVE FIXED THRUST GIMBAL
TOTAL FUNDS	247.79	295.89	270.65	225.72	229.75	267.02	258.84
NON-RECURRING	(110.20)	(133.19)	122.51	(100.20)	(91.49)	(125.28)	(122.70)
DEVELOPMENT	65.67	80.97	75.00	59.07	60.12	82.21	76.25
DELIVERABLE HDWRE.	15.51	18.36	17.33	13.09	13.15	16.01	15.51
OVERHAUL AND REFURBISH PARTS	9.79	12.63	10.30	8.81	8.51	6.98	10.00
PROPELLANTS	19.23	21.23	19.88	19.23	9.71	20.08	20.94
RECURRING	(137.59)	161.65	148.14	(125.52)	(138.26)	(141.74)	(136.14)
INVESTMENT	(56.03)	(70.99)	(61.30)	(48.21)	(52.79)	(56.00)	(56.00)
DELIVERABLE ENGINES	46.73	61.50	52.13	39.40	42.37	46.70	46.70
GSE	0.76	0.80	0.78	0.72	0.86	0.76	0.76
INITIAL SPARES	7.85	7.80	7.70	7.40	9.07	7.85	7.85
ACCEPTANCE PROPELLANTS	0.69	0.89	0.69	0.59	0.49	0.69	0.69
OPERATIONS	(81.56)	(90.66)	(86.84)	(77.31)	(85.47)	(85.74)	(80.14)
FLIGHT SUPPORT	23.08	24.7[illegible]	24.00	23.08	23.05	23.85	21.98
OPERATIONS	30.04	30.02	30.46	28.02	36.12	30.64	[illegible].38
OH AND REFURBISH PARTS	28.06	35.50	32.00	25.83	25.99	30.87	28.40
PROPELLANTS	0.38	0.38	0.38	0.38	0.28	0.38	0.38
DIFFERENCE IN $	BASE	47.26	22.86	-22.07	-18.04	19.23	11.05

445 FLIGHTS - 45 PER ENGINE - ALL ACTIVE PARTS REPLACED ONCE

2/19/72

in injector costs from that of conventional engines.

The maximum success program with some parallel development effort indicates the possibility of an 8/1/77 FMOF at a program cost of 267.02\overline{M}$. An additional program schedule of 9 months for the most probable program results in a cost of 258.90\overline{M}$.

The configurations listed are based on:

Thrust Levels:	600,000 lbs and 1,200,000 lbs
Chamber Pressure:	250 psia
Expansion Area Ratio:	5:1
Propellants:	LOX/RP
Overall Mixture Ratio:	2.4:1
Cooling Configuration:	Regenerative; Duct
Throttling Capability:	None, Continuous to 70% of Thrust
TVC System:	LITVC, Gimbal 2 Axis, Head End Pivot

The assumptions used were:

1. Refurbishment (primarily checkout and replacement of components on vehicle limited overhaul)
2. No cost for removal of engine from vehicle
3. Cost FOB TRW Systems
4. Spares
   a) Parts for deliverable engines, one percent of active components
   b) Operational spares calculated as:

      Cost of delivered engine times percent of active components

      For 445 flight program assumed that each active component would on the average be replaced once (100%)

      For reduced flight program spare parts assumed to be reduced by the logarithm of the number of uses per engine

      Some adjustment for higher rates early in the program
5. Product assurance included in hardware costs
6. Engine will be shipped as a fully integrated assembly
7. Cost for launch site prior to FMOF in RDT and E
8. Cost through fee (price)

The PFE program approach taken by TRW has a reduced number of critical definition dates in the overall program. These are as indicated in Table 3.6-2.

Table 3.6-2. Critical Definition Dates

		FROM ATP	CRITICAL CDR CONFIGURATION RESTRAINT
ENGINE			
o PROPELLANT LINE INTERFACE		18 MONTHS	BELLOWS FOR GIMBAL
o ENGINE MOUNT		18 MONTHS	FABRICATION TIME
o TVC SELECTION (REQUIRES PARALLEL DEVELOPMENT)		13 MONTHS (LITVC) 15 MONTHS (GIMBAL)	CHAMBER ASSEMBLY
FACILITY ACTIVATION			
o EAFB	2A (COMPONENTS)	AT ATP	SET UP, REFURBISHMENT TIME
o EAFB	1B	AT ATP	TANKAGE (8 MONTH LEAD TIME)

4. SUPPORTING RESEARCH AND TECHNOLOGY REQUIREMENTS

The TRW PFE approach as selected maximizes the advantages of a state-of-the-art approach and minimizes the scope of supporting research and technology requirements. Because it is a new engine with long service life, there are certain unknown areas which require supporting research in order to finalize the design approach. These areas are summarized here. Most can be accomplished in 9 to 12 month analytical and experimental programs. The derived data would be directly applicable to PDR phases in the development program.

4.1 INJECTOR

Status

The scaling of the coaxial pintle injector to 1,200K represents a significant size step in its application. The largest size unit ever test fired was at 250K thrust, 300 psia with earth storables under Air Force sponsorship. The largest unit test fired with LO_2/RP-1 was 50K at 250 psia. In no case has it been possible to drive the unit unstable, and its performance has been adequate for the pressure fed booster application. The approach has been throttled 5:1 mechanically in a larger size (250K), and, it has been pressure throttled 30% from 300 psia without incurring chugging problems. The type of testing required is not that for a significant technological break through, but more of verification of approach.

Justification

The primary unknown in the appraoch is associated with its ability to be scaled to 1,200K while retaining its previously demonstrated stability and performance characteristics. Previous large engine scaling difficulties have been well documented for comparison (F-1, M-1).

Technical Approach

The objectives of this task would be to investigate the following areas with the indicated techniques.

Area	Technique
• Stability, High Frequency	Uncooled 1,200K boiler plate chamber Bomb and pulse gun
• Low Frequency	Uncooled 1,200K boiler plate chamber, feed system simulation, pulse feed system
• Pressure Throttle Limits	Pressure decay for limits • Minimum $\Delta P/P_C$ • Pulse System
• Performance Scalability of TRW Coaxial Injector	Uncooled, cooled chambers - simulate fuel temperature, short duration • 250,000 lbf scaling • 1,200K boiler plate • L/D segment additions • MR, P_C sweeps • ΔP requirements

This effort would require a 12 month technical effort.

4.2 IGNITION

Status

The selected means for ignition of the PFE is by hypergol slug similar to that used in the F-1. The 1,200K PFE is the largest device yet conceived which requires an auxilliary ignition source. As a large device the requirements for a safe ignition of LO_2/RP-1 must be carefully determined by synthesis of theory and empericism. Successful TEA ignition of LO_2/RP-1 has been conducted in a 50K LO_2/RP-1 PFE. The F-1 has also been ignited by TEA/TEB when operated as a PFE at high pressure.

Justification

The primary unknown area associated with the PFE ignition requirements is that of sequencing the propellants and hypergol into the large PFE chamber. The coaxial injector is sufficiently different from the F-1 to necessitate an investigation of the candidate ignition system.

Technical Approach

The ignition requirements would be determined by conducting a series of ignition tests in boiler plate hardware at both 250K and 1,200K thrust levels. The quantity of hypergol, the number of required points of injection, and the amount of fuel flush required to accomplish the ignition safely would be determined from various sequences.

4.3 MAIN VALVES

Status

The main valve requirements are not particularly stringent or burdensome to the designs. However, the valves are large, and they have full tank pressure heads locked up behind them at ignition. At thrust termination command to shut off they must adequately seal the propellant flows, again with high tank pressures behind them. Commercial use of the type of valves contemplated indicates no problem in repeated actuation for the number of cycles contemplated for the Space Shuttle. The usual commercial environment does not, however, have a sizeable g-field imposed on it. The repeatability of the valves to meet precise start/stop transient requirements has never been demonstrated. None of these valves have ever been cyclicly exposed to sea water.

Justification

The high pressure loadings combined with the resultant high seat loads, aerospace flight requirements to withstand given g-fields and start/stop transients necessitate an investigation of the basic design for the Space Shuttle application.

Technical Plan

Since the basic design approach requires some verification, configurations for both the LO_2 and RP-1 would be acquired and the following investigations carried out.

Area	Technique
• Cyclic seal life	Cycle simulated seal to full duty cycle with propellant
• Unit seal loads	• Cryogenic sea water exposure • Simulate loads

This requires an 8 month technical effort.

4.4 THRUST CHAMBERS

Status

The cooling concept itself is state-of-the-art. The Atlas, H-1, F-1 background data is sufficient for the design of the thrust chambers from a coolant point of view. The life and exposure environment cyclic effects have never been proven for the mission requirements of Space Shuttle. Sea water exposure effects have been only briefly investigated. An H-1 engine was given a minimal exposure to sea water, carefully taken apart, cleaned, reassembled and fired; however, this exercise was a long ways from the desired operational philosophy of the Space Shuttle vehicle. The long term effects of repeated cycling of corrosion are largely unknown.

Justification

The realization of the full cost savings potential of the Space Shuttle concept requires that the TCA exhibit full mission capability with a minimum of refurbishment and replacement. The unknown effects of sea water quenching, following full thermal cycling, followed by cyclic exposure to the atmosphere and sea water require investigation to gain confidence in the design and fabrication techniques.

Technical Approach

It is suggested that most of the required data can be acquired with a smaller PFE on the order of 50,000 lbf. This unit would be thermally cycled through its life and salt water quenched after each firing. In addition, the chamber would be periodically exposed to 24 hours of sea water immersion, drained, flushed and refired. Careful physical examination of the chamber along with the use of strain data and pressure proofing tests would provide data for design purposes. Following the final tests, the chamber would be purposefully pressure ruptured to determine its final margin. In addition, the tubes would be sectioned to determine long term, if any, deleterious effects of coking and sea water exposure, both internally and externally.

4.5 FUEL SYSTEM COUPLING

Status

All vehicle designs recognize that the pressure gain ratios for the PFE stage are considerably larger than for a pump fed engine. Because of a POGO susceptibility on S-1C and this high gain ratio, there exists some question as to the designer's ability to synthesize a reliable pressure fed stage. However, there are a number of missile pressure fed systems flying. In addition, the delivery ends of the Apollo vehicle, the Command Service Module, the descent and ascent stages are all pressure fed and fly without difficulty.

The problem on S-1C was alleviated by use of a capacitance in the feed system. This fix was virtually dictated by the fact that the stage design was completed when the problem was discovered. It was not necessarily the most optimum.

Justification

Low frequency propellant system coupling with the PFE can lead to destruction of the stage or an unacceptable g-loading on personnel or components. The asertion that the TRW PFE has a stabilizing influence on such coupling requires verification.

Technical Approach

The developed analytical tools are adequate to investigate this problem area to aid in the design of the overall stage. Actual detailed dynamic response analysis would be conducted for the PFB. A direct comparison would be made with the S-1C problem, in order to provide an assessment of the problems of low frequency coupling.

4.6 OVERALL DEVELOPMENT RISK ASSESSMENT

The conservative design approach taken with the TRW PFE results in a high confidence that the PFE can be developed within the Space Shuttle time reference requirements. Because of its cimplicity and the maximizing of state-of-the-art procedures and materials selections, the cost estimates of such an effort can be looked upon with a high degree of confidence. The primary development effort can then be directed to a demonstration of life and the development of low cost fabrication and maintenance procedures.